Advanced Transportation System Studies

Technical Area 3

Alternate Propulsion Subsystem Concepts
NAS8-39210
DCN 1-1-PP-02147

SSME Upper Stage Use
Task Final Report and Briefing
DR–4
March 1993

ROCKETDYNE

Rockwell International
Rocketdyne Division

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TA3–0299

SSME Upper Stage Use
Objectives

The main objective of this study is to determine if the SSME can be used in an upper stage application in which an altitude burn for earth orbital insertion and an orbital translunar injection burn may be required. The SSME currently operates and performs cut off in a space environment; however, it starts at sea level in an ambient atmosphere. Also, the current tank pressures are higher than would be desirable for an upperstage. The key goals of this study are to determine viable methods for starting the SSME in an altitude environment and restarting it in an orbital environment with minimum changes in utilization of the engine system or hardware.

A common start sequence for both altitude and orbital conditions is a key objective of the study. By maintaining a common start sequence development costs can be minimized. On the other hand, the impact to the stage design of a common start sequence could potentially be prohibitive by increasing stage complexity to support a common engine start sequence. Therefore, the development cost and schedule impact must be traded between the propulsion system and stage design.

SSME Upper Stage Use
Objectives

- **Determine Methods to Ensure an Altitude Start and an Orbital Restart for the Current SSME**
  - **Altitude Upper Stage Use**
  - **Trans Lunar Injection from Low Earth Orbit**
- **Develop a Common Start Sequence for Both Conditions if Feasible**
- **Determine Impact**
  - **Stage**
  - **Engine**
    - **Development**
      - **Schedule**
      - **Cost**

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SSME Upper Stage Use

Topics

- Requirements
- Current SSME Start Sequence
- Altitude Start
- Orbital Restart
    - Orbital Coast Phase Thermal Analysis
    - Orbital Restart Analysis
- Conclusions
    - SSME Impacts
    - Stage Impacts
    - Cost and Schedule
- Recommendations for Further Work

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Requirements

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SSME Upper Stage Application
Duty Cycle Scenario

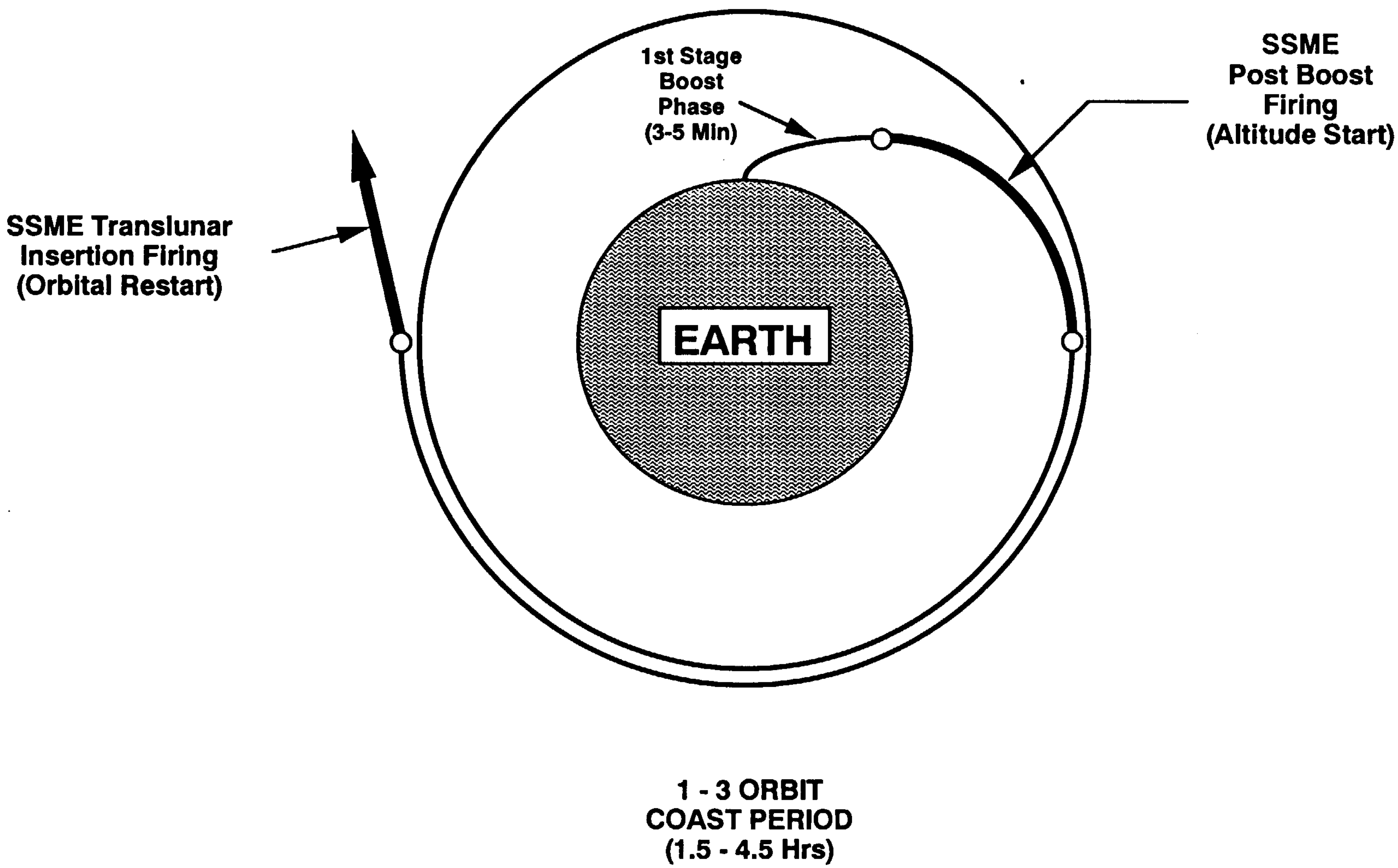
The scenario which has been defined in related vehicle studies for using a SSME engine in an upper stage involves an altitude start and an orbital restart.

For the altitude start, the engine is used shortly after launch during upper stage operation for a sub orbital burn to establish an orbit. The orbital restart is used for a later trans lunar injection burn.

The orbital restart analysis examined orbital coast times ranging from 1.5 to 4.5 hours (1 to 3 revolutions) based on the Apollo vehicle S-IVB stage experience and recent vehicle study information. Shorter and longer times were examined as excursions.

The orbital restart differs from the altitude start in the starting thermal conditions for the engine components and in that fluid has flowed through the engine thus changing the potential contaminant conditions for engine components at restart versus initial start.

SSME Upper Stage Use
Duty Cycle Scenario



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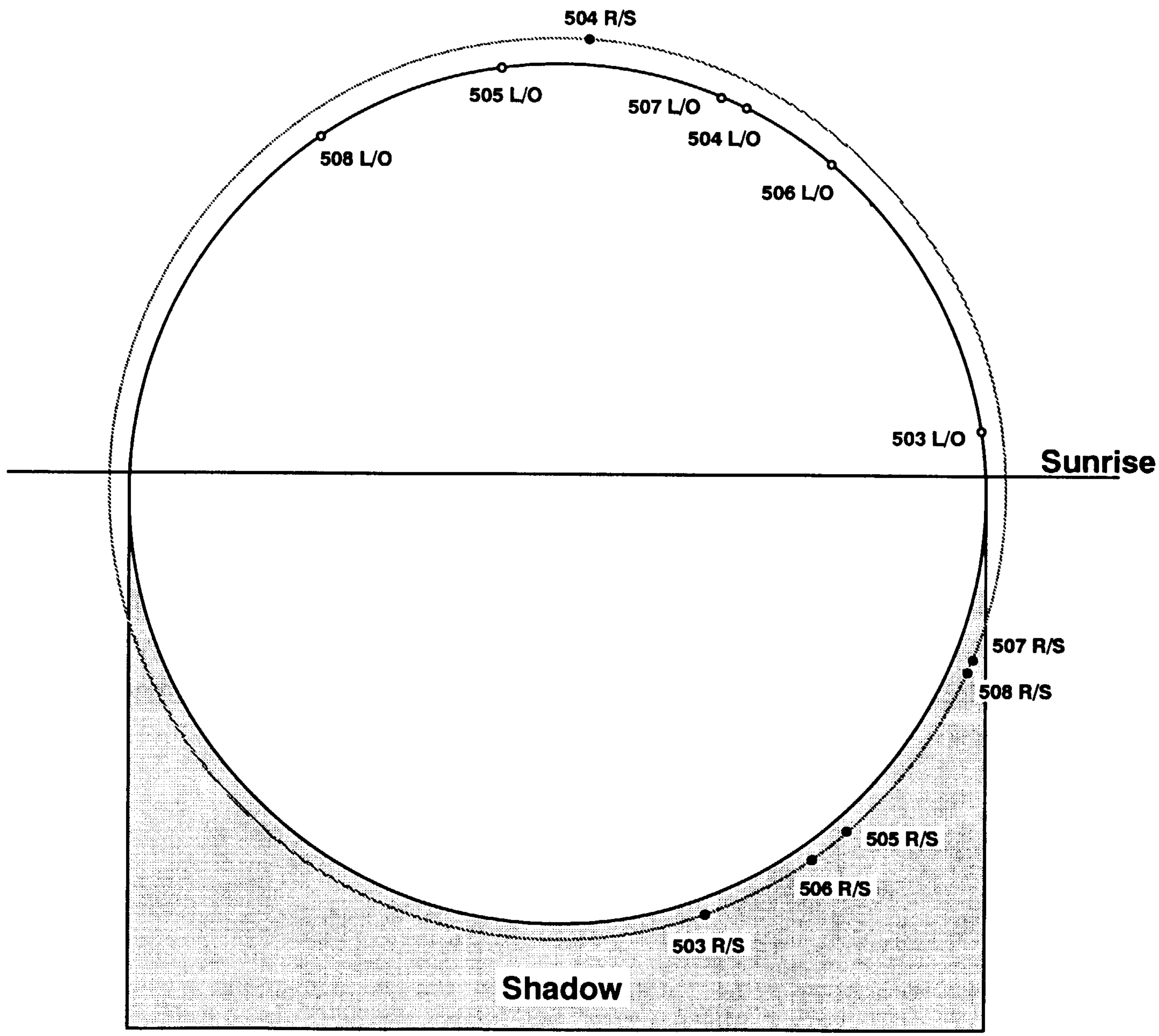
SSME Upper Stage Use

Apollo Launch and Restart Positions

During the Apollo program restart of the SIVB stage occurred on both the shadow and solar sides of the earth. Data for six of the Apollo missions that were conducted by the U. S. space program show both vehicle positions at lift-off from KSC and for the restart of the SIVB stage with respect to the location of the earth's shadow. All six lift-offs took place on the solar side of the earth while five of the six restarts took place on the shadow side. It can be determined from this data that design of the SIVB stage allowed critical operations such as restart of the single J-2 engine to be carried out at any position around the earth. The lack of solar radiation on the shadow side of the earth can potentially create reduced hardware temperatures which can influence the restart characteristics. The reverse is also true, the increased radiation on the solar side can increase hardware temperatures and influence restart characteristics.

SSME Upper Stage Use
Apollo Launch and Restart Positions



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SSME Upper Stage Use
Apollo Experience

Based on the Apollo experience a threshold time to restart can be derived to allow the engine hardware to reach specific thermal conditions that would provide sufficient energy for restart whether on the solar or shadow sides of the earth. A minimum of approximately two hours and 20 minutes was available to raise temperatures to levels satisfactory for restart. A maximum of approximately 4 hours and 30 minutes was experienced prior to restart for Apollo 9.

Consequently, an Apollo type of mission profile would require that the engine be capable of restarting from around two hours after orbit insertion and all subsequent time. Shorter times could be needed for other mission profiles and a one hour restart time was also examined.

SSME Upper Stage Use
Apollo Experience

Mission	Apollo	J-2 Restart Seconds After Orbital Insertion
AS503	8	9,534
AS504	9	16,472
AS505	10	8,485
AS506	11	9,139
AS507	12	9,333
AS508	13	8,578

- Restart After ~8400 Seconds (2 Hours – 20 Minutes)
- Restart Between $1\frac{1}{2}$ and 3 Orbits

SSME Upper Stage Use
SSME Start and Restart Considerations

Successful ignition of topping cycle, pump fed liquid propellant rocket engines requires that several key parameters are within nominal ranges prior to beginning, and during, the ignition sequence. For the SSME, the nominal sequence for ignition was developed with ambient temperature conditions for most of the engine components except those requiring preconditioning with cryogenic propellants. The main concerns are controlling the combustion processes during ignition and until transient conditions have been overcome in the engine components to avoid hardware damage. Numerous parameters must be held within acceptable ranges with respect to one another and with respect to absolute valves. In general, the key parameters to accomplishing a successful start are mixture ratio, propellant masses, turbopump speeds, pressures, and pump inlet temperature.

Specific goals of this study were to develop an altitude start and orbital start sequence as close to the SSME experience base as possible, to strive to minimize unburned hydrogen expelled from engine, and to ramp up the engine power level as soon as possible. Pursuing these goals provides minimum development risk in the transient operation of the engine and prevents safety hazards and wasting propellants in the vehicle.

To stay as close as possible to the SSME experience base, a set of basic groundrules from lessons learned in the past were established. Maintaining a similar mixture ratio sequence during start was the guiding rule. To achieve this, the first component in the engine to ignite is the fuel preburner (FPB) which must light within 0.7 seconds of the start signal to prevent the high pressure fuel pump from stalling. Once the FPB has ignited, the Main Combustion Chamber (MCC) must ignite prior to MCC priming to prevent detonation which can result in major component damage or adverse engine operating conditions such as high back pressure on the turbines which drive the high pressure fuel and oxidizer pumps. Maintaining mixture ratios within a range defined by the extensive SSME experience base keeps the sensitivity of component variations within manageable limits so that temperatures can be successfully controlled in the engine components. The oxidizer preburner must prime after the MCC priming to provide enough back pressure to the high pressure oxidizer turbine so that the speed can be maintained at safe levels. Similarly, the priming of the high pressure fuel pump must occur within approximately 0.1 seconds after the FPB is primed. In following these basic groundrules, a low risk start sequence was investigated.

SSME Upper Stage Use
SSME Start and Restart Considerations

- Achieve Start and Avoid Hardware Damage
    - All Components Operate Within Nominal Limits of Speed, Pressure and Temperature
    - Stay Close to Mixture Ratio Sequence During Start (i.e., Temperature Sequence)
        - Fuel Preburner Ignition Needs to Occur Within 0.7 seconds of Start Signal
            - Prevent Pump Stall
        - Main Chamber Ignition Needed Before Main Chamber Prime
            - Avoid Detonation
            - Lower Pressure Pulse
            - Lower Back Pressure on Turbines
        - Maintain Hydrogen Rich Conditions (Temperature Issue)
            - Fuel Preburner Prime Before Main Chamber
                - Assure Fuel Flow at Turbine Back Pressure Increase
            - Oxidizer Preburner Prime After Main Chamber
                - Oxidizer Pump Easy to Overspeed
        - Prevent Excessive Fuel Pump Speed at Main Chamber Prime
            - Main Chamber Prime ~0.1 second After Fuel Preburner Prime
                - Load Fuel Pump
- Minimum Unburned Hydrogen Expelled from Engine (Safety Issue)
- Start Time as Short as Practical
- Stay Close to SSME Experience Base

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Current SSME Start Sequence

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SSME Upper Stage Use

SSME Flow Schematic

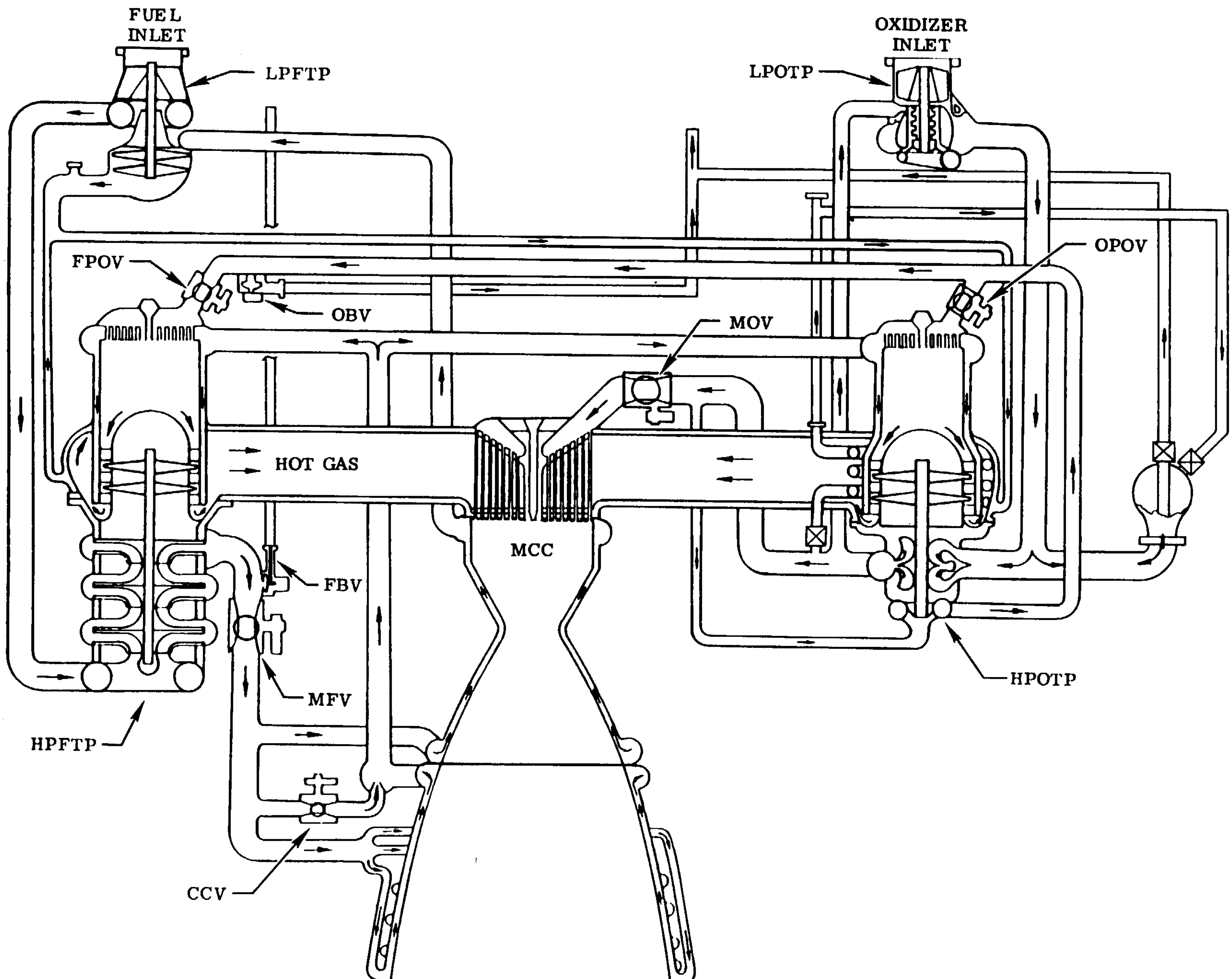
The facing page shows a schematic diagram of the major SSME components and the inter-connect ducting which conveys liquid cryogenic propellants and hot/cool gases to and from components. The propellants initially enter the engine in inlet ducts from the vehicle propellant tanks into the preconditioned fuel and oxidizer low pressure turbopumps which boost the propellant pressures enough to allow high speed, high pressure pumps to efficiently produce high discharge pressures for the 3000+ psia main chamber pressure of this staged combustion cycle engine. The propellant discharged from the HPFP is fed into three main parallel circuits which eventually recombine in the MCC to be mixed andcombusted. The first circuit from the HPFP feeds the MCC coolant liner and powers the low pressure fuel turbopump turbine prior to cooling the hot gas manifold which directs the HPTP turbine discharge to the main injector. The cooling circuit combines with the remainder of the fuel in between two of the injection face plates. The second circuit discharging from the HPFP is actually a bypass leg from the nozzle cooling circuit which is the third HPFP leg and is recombined with the nozzle coolant in a jet pump type mixer down stream of the nozzle regenerative coolant circuit. The mixed hydrogen is gaseous and enters both preburner injectors where it is mixed with LOX to be combusted at fuel rich mixture ratios to produce hydrogen rich steam to drive the HPTP turbines. As the gas is discharged from the turbines, they are fed to the main injector for combustion in the MCC.

The oxidizer discharged from the LPOP is routed to the main oxidizer pump and to a pogo suppression device which is pressurized by a branch of the oxidizer heat exchanger used to primarily pressurize the vehicle LOX tank. Pogo pressure is regulated by an oxidizer bleed line.

The LOX pressurized by the HPOP is routed to the main oxidizer valve which feeds the LOX dome of the main injector. However, a portion of the LOX discharged from the HPOP is split into two circuits, one of which feeds a boost pump that feeds the LOX for both the fuel and oxidizer preburners. The other circuit is fed back to the LPOTP to drive the LPOT where it is recirculated to the low pressure oxidizer pump discharge. Approximately 17% of the LOX is recirculated through the HPOP to drive the LPOTP turbine. A small amount of LOX is tapped off the main oxidizer valve supply duct to provide pressurant for the vehicle LOX tank. The LOX tap provides LOX to the heat exchanger coils located down stream of the turbine. Seven key valves provide control of the propellants in the engine. The main valves for both fuel and oxidizer along with the two preburner oxidizer supply valves, the coolant control valve, and the two by-pass valves.

SSME Upper Stage Use

SSME Flow Schematic



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SSME Upper Stage Use
Functional Sequence of Start

The start sequence for the SSME involves two main phases of operation.

The first is when the engine is being prepared to start, the second is when ignition takes place and mainstage operation begins.

The preparation phase has two main goals. The engine components must be cleared of any residual gases which could adversely affect the start. A purge sequence is used to clear and maintain known environments in the engine. During the purge, thermal preconditioning of the pumps and interconnect ducting upstream of the main propellant valves is accomplished by recirculation on the fuel side and bleeding on the oxidizer side to maintain stable and cold enough temperatures to insure sufficient net positive suction head for the pumps to operate correctly.

The start phase has an initial mode of operation in which the engine is controlled in an open loop schedule to open propellant valves, terminate purges, stop recirculation and bleeding for thermal conditioning, excite igniters, and begin close loop control based on thrust.

The second mode of the start phase is when thrust build-up is accomplished along with MCC ignition detection which is checked by measurement of the chamber pressure with respect to a reference range. The method of control of mixture ratio is activated to closed-loop for both the preburner oxidizer valves. Open loop control schedule is continued for the main fuel valve (MFV). The main oxidizer valve (MOV) and the coolant control valve (CCV) continue as open loop until the mainstage mode is achieved.

SSME Upper Stage Use
Functional Sequence of Start

- Prestart Preparation Phase
    - Purge Sequence Conducted
    - Engine Thermal Conditions for Start Attained
- Start Phase
    - Initiation Mode
        - Propellant Valves Opened
            - Open Loop Control Schedule
        - Purges Off
        - Bleed Valves Closed
        - Igniters Energized
        - Thrust Control Loop is Closed
    - Thrust Buildup Mode
        - Ignition Detected by Main Chamber Pressure
        - Closed Loop Thrust Buildup Sequence Initiated
        - Mixture Ratio Control Loop is Closed
        - Open Loop Control Schedule Continues for MFV, MOV, CCV Until Mainstage
    - Mainstage Established

SSME Upper Stage Use
Current Start
System Constraints/Control Scheme

Control of the SSME during initial transient operations begins with open loop preprogrammed scheduling of the main fuel valve, main oxidizer valve, the oxidizer preburner oxidizer supply valve, the fuel preburner oxidizer supply valve, and the coolant control valve. Engine parameters which are used for closed loop control during main stage cannot be used since the values are too low to accurately measure. In addition, the physical characteristics of the propellants are rapidly changing as they initially pass through the major components making initiation of some key events, such as priming or temperature spikes, virtually impossible to detect until the event occurs.

Once the engine operating level is high enough, a closed loop control mode for the MCC pressure (thrust limiting) is activated at 0.74 seconds which utilizes proportional error only to influence the position of the OPOV. This mode provides partial control of the chamber pressure prior to 2.4 seconds, so that if a fuel leak occurs downstream of the fuel flow meter, mixture ratio will be limited from going to catastrophic hardware damaging levels. Full closed loop control (proportional and integral) of the MCC pressure (thrust) is activated at 2.4 seconds after the start signal. Mixture ratio control is still open loop at this time. At 2.4 seconds the command thrust level being controlled by the OPOV begins ramping to mainstage.

The FPOV controls mixture ratio of the engine during higher levels of engine operation and mainstage. At 0.80 seconds after the start signal, a cross-feed gain is established from the OPOV position to the FPOV position to minimize mixture ratio variations due to power level changes during ramp up. In the event that a lock-up would occur, large mixture ratio variations could be extremely detrimental. By using the cross-feed gain between the OPOV and FPOV, mixture ratio variations are small. Full closed-loop control of mixture ratio is activated at 3.6 seconds, just prior to the engine reaching mainstage.

Mixture ratio control during the initial stages of engine is conducted by establishing propellant temperature and pressure within acceptable ranges at the inlets to the pumps prior to and during start. The temperatures of the pumps, as well as other key components, must be within defined temperature ranges as well since they significantly influence the properties of the propellants which initially pass through the engine during the start phase. Temperature variations during the start phase do not correspond directly with the key events occurring in the engine and, therefore, would not be an effective control parameter.

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SSME Upper Stage Use
Current Start
System Constraints/Control Scheme

- Initial Part of Sequence Uses Open Loop Positioning of Valves
    - Main Fuel (MFV), Main Oxidizer (MOV), 2 Preburner Oxidizer (OPOV, FPOV), Coolant Control (CCV)
    - Preprogrammed Schedule of Valve Positions
    - Control Parameter Values are Too Low to Measure Accurately
    - No Indication of Some Key Events Such as Priming or Temperature Spikes Until Event Occurs

- As Engine Operating Levels Increase Closed Loop Control Can Begin
    - Closed Loop Thrust Control Mode
        - Main Chamber (Proportional Error Only) at 0.74 Seconds
            - Provides Partial Chamber Pressure Control Prior to 2.4 seconds
                - Chamber Pressure Influences OPOV
        - Full Closed Loop Control of Main Chamber (Proportional and Integral) at 2.4 seconds
            - Full Closed Loop for Thrust Only, Not Mixture Ratio
        - Main Chamber Pressure (Thrust) Controlled by OPOV
            - Command Pressure Ramped to Mainstage at 2.4 seconds
    - Mixture Ratio Controlled by FPOV
        - After 0.8 seconds Cross Feed Gain from OPOV to FPOV to Provide Acceptable Mixture Ratio During Ramp to Mainstage
        - Closed Loop Mixture Ratio Control of FPOV Activated at 3.6 seconds Just Prior to Engine Reaching Mainstage

- Mixture Ratio Control
    - Assumes
        - Inlet Conditions Within Specific Temperature and Pressure Ranges
        - Certain Components Within Specific Temperature Ranges
    - No Control Through Measured Preburner or Turbine Temperatures
    - Preburner Augmented Spark Igniters (ASIs) Controlled be Orificing of Lines – Not by Valves

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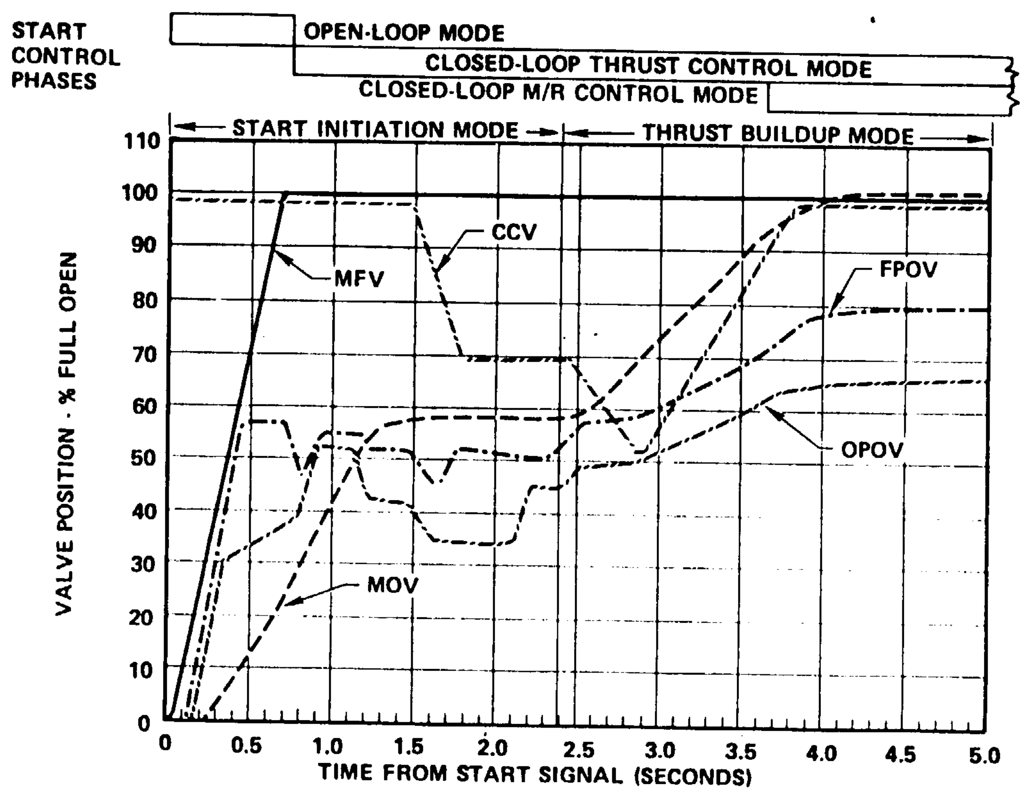
SSME Upper Stage Use
Engine Start Valve Sequence (Typical)

The diagram shown is the valve position sequence for the nominal start of the SSME. The valves are ramped initially by open-loop schedules until the MFV reaches full open position at which time the closed-loop thrust control mode is actuated. The MFV leads the oxidizer valves in the initial ramp to provide a fuel rich lead to the combustion components. The FPOV leads the OPOV and MOV since the fuel preburner is the first to ignite. The ramp-to-value is higher so priming occurs sooner to provide sufficient power to bring the HPFTP up to speed. The OPOV is ramped prior to the MOV for ignition, however, the ramp-up is slower and to a lower value so that the priming of the oxidizer preburner occurs after the main chamber. Notches are incorporated into the FPOV and OPOV valve position schedule to minimize temperature spikes in the turbines. Once the engine is operating smoothly with stabilized temperatures and both preburners and the main chamber primed, the thrust buildup mode is initiated.

The CCV is open to near 100 % at the beginning of the start initiation mode so that hydrogen can bypass the nozzle and arrive at the preburners as soon as possible for boot-strapping of the turbines. When the main chamber primes, the CCV ramps down to provide higher coolant flow through the regenerative nozzle to prevent wall temperatures from rising above desirable levels at the lower power levels. Closed-loop mixture ratio control is activated near the end of the thrust build-up ramp.

SSME Upper Stage Use

Engine Start Valve Sequence (Typical)



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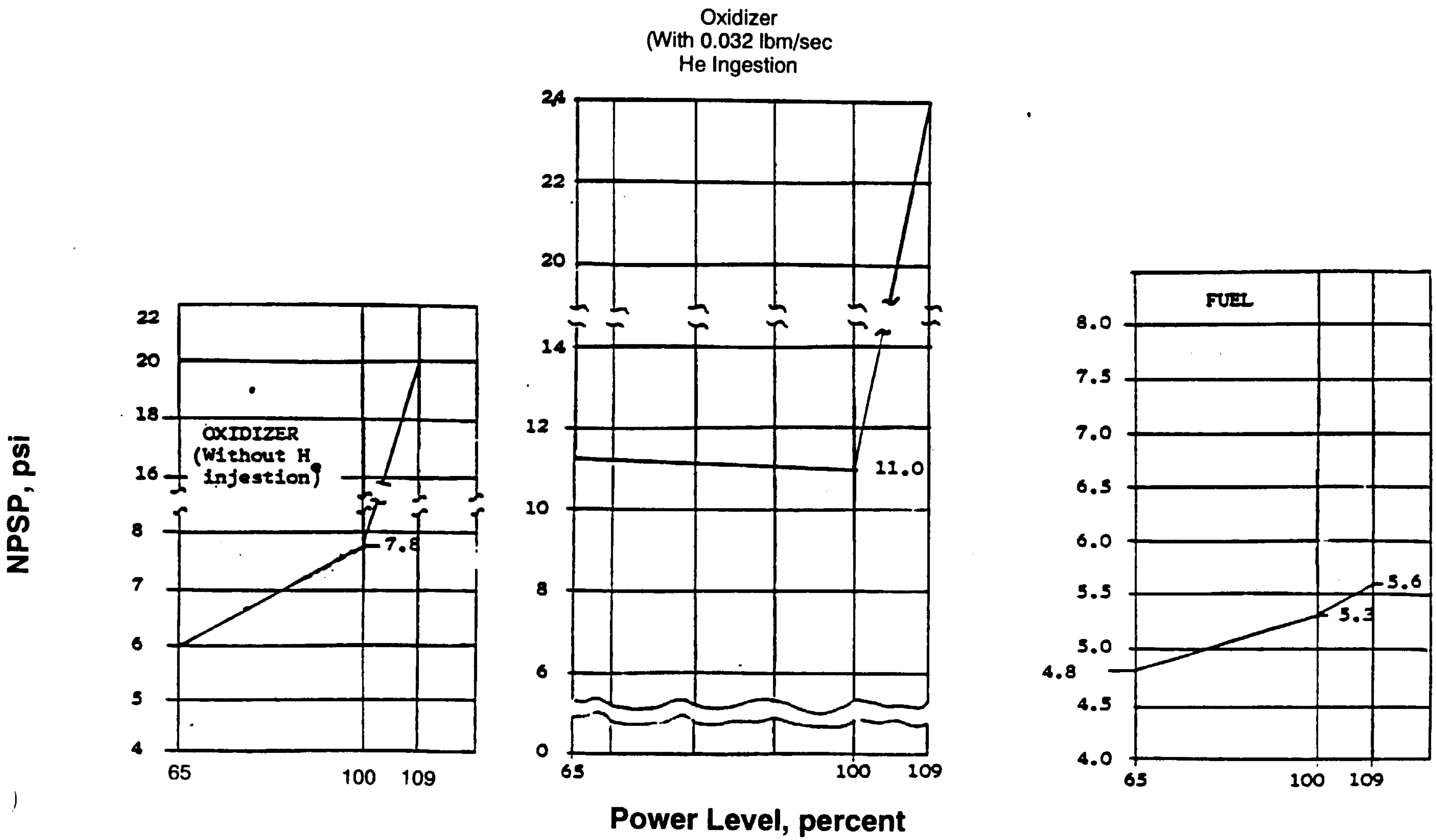
SSME Upper Stage Use
Pump NPSP

If fluid static pressure at the pump inlet or any region within the pump drops below the fluid vapor-pressure cavitation will occur which can effectively change flow passages and create flow instabilities that could result in substantial damage.

By maintaining sufficient pressures at the pump inlet, cavitation can be avoided during operation. Net Positive Suction Pressure (NPSP) is the additional pressure required above the propellant vapor pressure to operate the pump with desirable operating conditions. Minimum NPSP requirements for the engine inlets vs. power level are shown in the diagrams on the facing page for both LOX and LH_2. An additional plot is shown for the LOX inlet with a maximum helium ingestion rate of 0.032 lbm/sec to account for ingested helium returned from the engine accumulator (POGO) to the vehicle LOX feedline. The SSME start is not impacted by the helium ingestion requirement because entrainment of helium does not occur until 5.0 seconds after the engine start signal.

SSME Upper Stage Use
Pump NPSP



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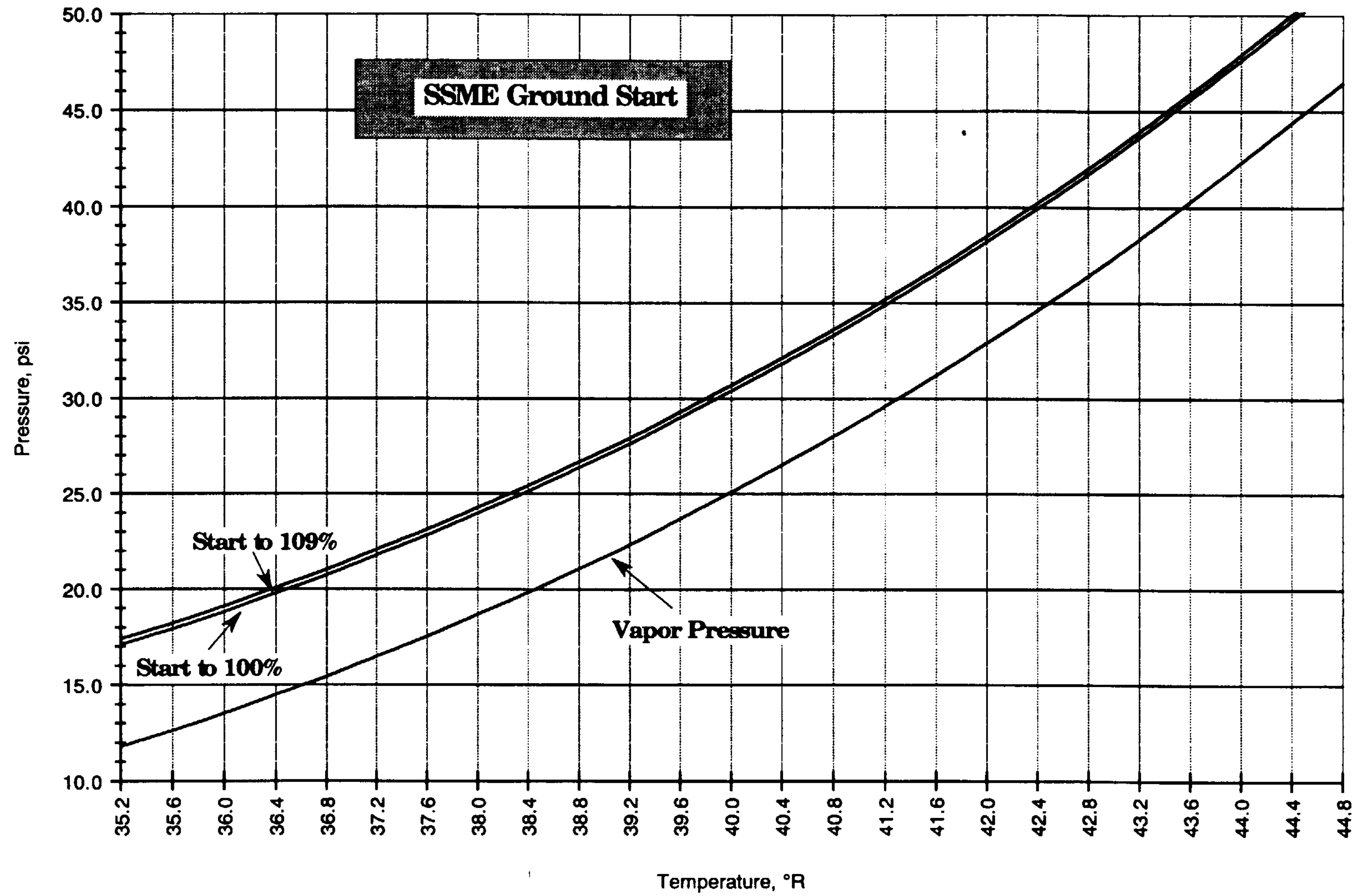
SSME Upper Stage Use
Fuel Conditions for Ground Start

Applying the NPSP requirements of the Low Pressure Fuel Pump to the LH_2 vapor pressure curve defines the minimum propellant supply pressure which must be provided. Pressure requirements for 100% and 109% power levels have been plotted. Also shown is the box of allowable (and expected) pressures and temperatures for the current SSME ground start. This is shown as a box in the upper left portion of the chart. For ground start of the SSME, the minimum supply pressure from the LH_2 external tank for start is 44 psia. Ambient pressure to which the engine exhausts is 14.7 psia. For altitude start, the ambient pressure is approximately zero pressure; therefore, the fuel inlet pressure supplied from the vehicle could be reduced by 14.7 psi without significantly changing the engine start sequence.

Fuel Conditions for Start



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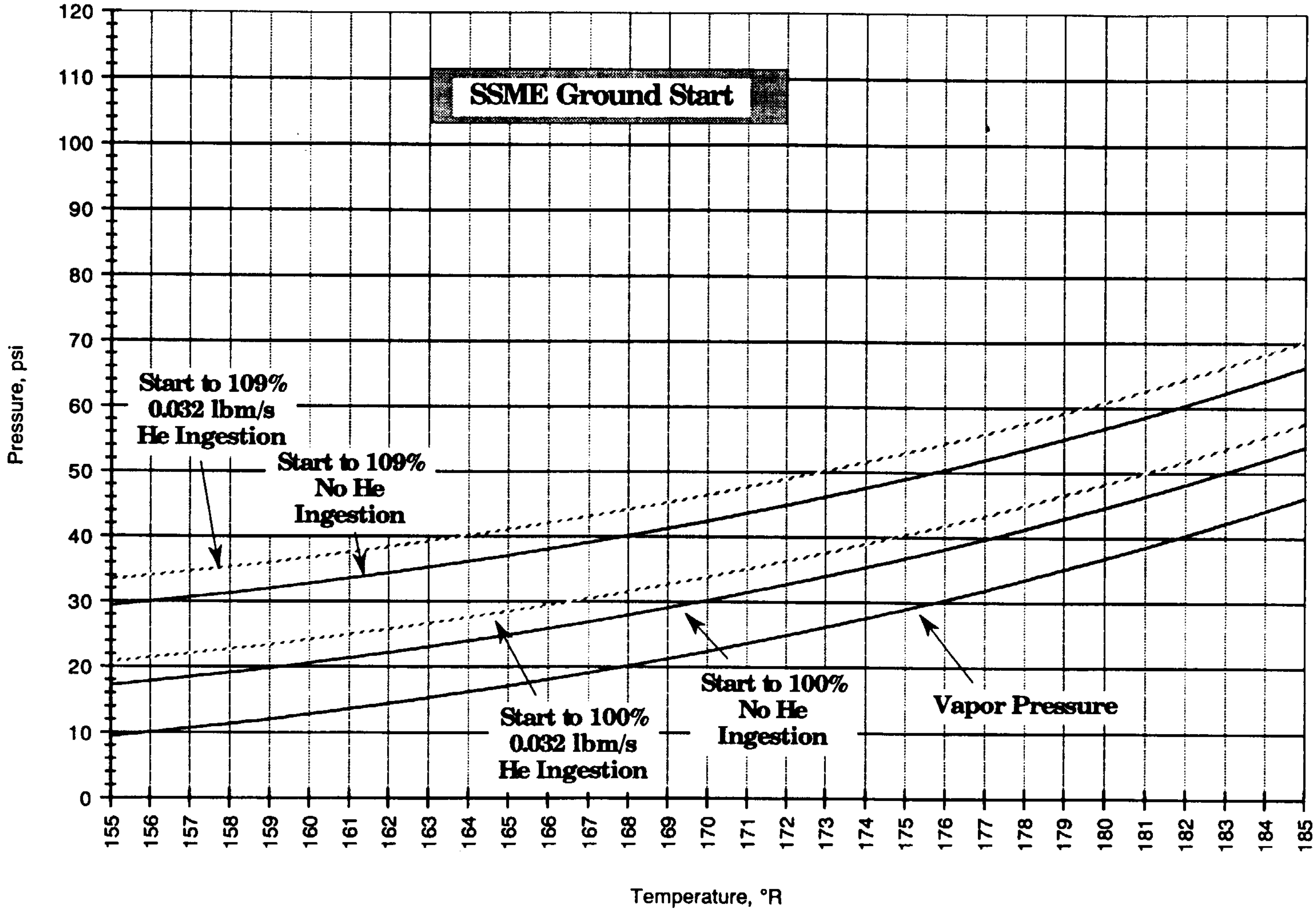
SSME Upper Stage Use
Oxidizer Conditions for Ground Start

This diagram is similar to the previous chart showing the requirements for the low pressure oxidizer pump inlet for ground start and the box of the current ground start conditions. The supply pressure is significantly higher than the pump supply pressure requirements due to the significant gravity head provided by the LOX tank position which is located on top of the LH_2 tank in the external tank. For upperstage application, the LOX tank pressure could be reduced significantly.

Oxidizer Conditions for Start



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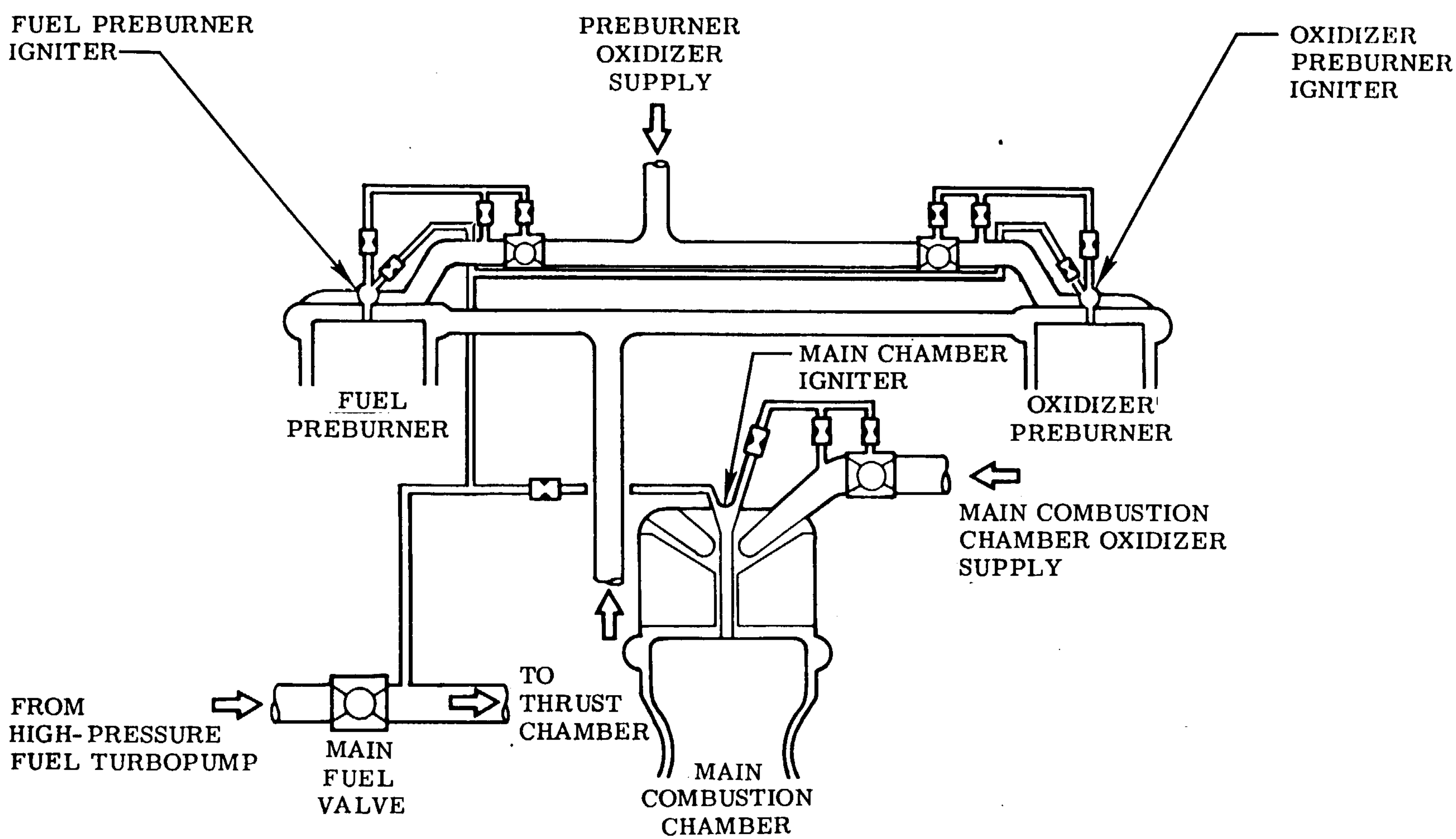
SSME Upper Stage Use
Augumented Spark Igniter (ASI)

The SSME start requires igniting the oxidizer preburner, fuel preburner, and Main Combustion Chamber. Ignition is accomplished with Augmented Spark Igniters (ASI) which have separate fuel and oxidizer supply lines that provide propellants during ignition and remain open for main stage contributing propellants for combustion along with the main supply lines. The mixture ratio for the ASI's is controlled by calibrated orifices in the ASI propellant supply lines. The fuel supply line flowrate is controlled by a single orifice for each igniter while the oxidizer system has a three orifice system for each igniter. The three orifice system is needed to accommodate the pressure and flow conditions created by the control valves for the oxidizer supply lines. During the early portion of the engine start, the LOX is supplied from the valve body supply line to provide oxidizer as quickly as possible to the igniter and at the correct mixture ratio to insure start. When the engine is just beginning to start the supply pressure is much lower than later in the start phase and during mainstage.

SSME Upper Stage Use
Augmented Spark Igniter (ASI)



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SSME Upper Stage Use
Impacts of Altitude Start and Orbital Restart on SSME Start Sequence

For the altitude start case, the thermal conditions are the same as the current ground start. However, the pressures are quite different. The gravity head is absent and both the fuel and oxidizer inlet pressures are reduced from the ground start case. More importantly the pressure reduction is not in the same ratio for both the fuel and oxidizer, which strongly affects underlying control assumptions of valve proportionality.

For the orbital restart case, the pressure conditions are different from the ground start case but they are similar to the altitude start case. But now it is the thermal conditions which are very different from the ground start case. The engine has been fired and shut down and the engine is in orbit which changes the thermal conditions from the ground start case. The change is not the same, in direction or amount, for all components. Different components are changed in different ways. Some are hotter than the ground case, some are colder. Consequently, the mixture ratio assumptions used in the control scheme are affected.

There is one additional impact for the restart case. The start environment of the engine has been changed from the ground start case because the engine has been fired and has been shut down in a vacuum. Water can be formed during the shut down and potentially form ice and change the start-up characteristics of the turbines. However, the combustion quenches after valve closure but before the purges during shut down and water formation is only possible during combustion. Additionally, vacuum means there is zero back pressure on the system and that the water vapor pressure is always above the pressure in the chamber and turbines. Consequently, water and ice formed may evaporate and/or sublime.

SSME Upper Stage Use

Impacts of Altitude Start and Orbital Restart on SSME Start Sequence

	Thermal	Pressure	Environmental
Altitude Start	• Same as Ground Start	• Lower Pressures • Changed Ratio of LOX/H2 Pressures	• Same as Ground Start
Orbital Start	• Engine Fired • Latent Heat • Solar and Earth Radiation • Heat Redistribution	• Same as Altitude Start	• Engine Fired • Moisture • Flow Path to Vacuum

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Altitude Start

TA3-0272

SSME Upper Stage Use

Groundrules and Assumptions for Altitude Start Analysis

The input conditions used for the altitude start case are based primarily on the Apollo program Saturn IV vehicle, S-IVB stage propellant inlet conditions and to a limited extent on engineering estimates of minimum pressures which would be viable for the operation of the SSME engine. The oxidizer inlet pressure is reduced from the shuttle external tank value of 107 psia (which is about 80 percent gravity head) to 40 psia, which was the value used on the S-IVB. The fuel pressure is reduced from 45 psia down to 32 psia which corresponds to a shift providing approximately the same delta pressure across the system (45 - 14.7 versus 32 - 0). In addition, 32 psia represents a lower bound with respect to fuel pump performance in that a margin must be maintained for NPSH above the vaporization pressure at the pump inlet to provide for engine and start variables.

The intent of the groundrules is to minimize adverse changes to the engine hardware or operation as well as minimize changes which would void the 500,000+ seconds of SSME experience base.

Engine operation for the altitude start occurs within five minutes of launch; therefore, changes in hardware conditions which influence the start are relatively small. The critical condition primarily being hardware temperature being near ambient. Confidence in this assumption is high since the engine hardware mass is greater than 7000 lbs which has soaked heat prior to launch and which is protected during the boost phase (aft skirt enclosure). The purges prior to altitude start are not foreseen as a significant driver to stage design since provisions for purges will already be required for safety purposes to avoid propellant accumulation in interstage connection compartments.

SSME Upper Stage Use

Groundrules and Assumptions for Altitude Start Analysis

- Input Changes
  - Prestart Inlet Pressures
    - Based on S-IVB Experience
    - Oxidizer Reduced From 107 to 40 Psia Nominal
    - Fuel Reduced From 45 to 32 Psia Nominal
  - Zero Ambient Pressure

- Groundrules
  - HPFTP Turbine Temperature Spike Equal to or Less Than Current Engine
  - HPOTP Turbine Temperature Greater Than Minimum Sustaining Combustion Temperature
  - Minimize Increase of Critical Phase Start Time (0 to 1.6 seconds)
  - Component Priming Order Maintained
  - Target Current Operating Levels of Critical Components at Prime
    - Speeds, Pressures, Temperatures

- Assumptions
  - Engine Hardware Conditions Same as For Current Ambient Start
    - Short Time for Changes to Occur
  - Standard Prestart Purges

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SSME Upper Stage Use
Altitude Start Analysis

Safely establishing and maintaining proper mixture ratios for the two preburners and the main combustion chamber (MCC) to ignite and sustain combustion is a key objective during the start phase of SSME operation. In lowering the inlet pressures of the propellants, the mass flow rates through the engine system are altered and hence change the mixture ratios at any given time up until priming of the oxidizer preburner. To achieve an altitude start sequence as close as possible to the current SSME, the valve schedule can be adjusted. Three key oxidizer valves, along with the main fuel valve, control the start sequence.The “Oxidizer Valve Positions” chart shows the changes in valve sequencing used for the altitude start case.

Additionally, the preburner and main combustion chamber igniter systems are supplied propellants by separate lines and will require reorificing to account for the lower inlet pressures.

The SSME transient start model was run with these changes and the results are shown in the “Main Combustion Camber Pressure” chart, the “Turbopump Speeds” chart, and the “Turbine Discharge Temperatures” chart. These charts should be examined along with the following discussion as they illustrate and detail the results.

The overall start result is shown in the “Main Combustion Chamber” chart where it can be seen that the initial bootstrap portion of the start is slower to begin, although it finishes at approximately the same time as the current start. A previously analyzed case using the Pratt & Whitney high pressure fuel turbine is also shown for comparison. As is implicit in the chart, the turbopumps are slower to begin their speed buildup as can be seen clearly in the “Turbopump Speeds” chart.

(Annotation continued on the next page).

SSME Upper Stage Use
Altitude Start Analysis

- Start Sequence Changes to Accommodate Lower Inlet Pressures

  - Approach
    - Adjust Valve Schedules
    - Reorifice Augmented Spark Igniter Propellant Supply Lines

  - Adjustments and Impacts
    - Fuel Preburner Oxidizer Valve (FPOV) Position Increased for First 1.0 Seconds
      - Maintain Adequate Mixture Ratio for Preburner Ignition
      - Slight Decrease in HPFTP Turbine Temperature Spike
        - Desirable to Reduce Hardware Damage Risk
    - Oxidizer Preburner Oxidizer Valve (OPOV) Position Increased During First 1.1 Seconds
      - Maintain Adequate Mixture Ratio for Preburner Ignition
      - Slight Increase in HPOTP Turbine Temperature Spike
        - Desirable to Increase Margin for Sustained Combustion
    - Main Oxidizer Valve (MOV) Initial Ramp Reduced from 60 to 55 %/second
      - Maintain Current Delta Time Between Fuel Preburner Prime and Main Combustion Chamber Prime

SSME Upper Stage Use
Altitude Start Analysis (Cont'd)

The results from the transient start model showed that opening the preburner oxidizer valves to a higher position (i.e., a larger percent open) was required during the first 1.1 seconds to provide adequate oxidizer flow to maintain proper preburner mixture ratios for ignition and speed buildup of the two high pressure turbopumps.

The slower speed ramp of the HPFTP delayed the fuel preburner prime therefore shortening the period before MCC priming. Consequently, in conjunction with the preburner oxidizer valve adjustments, the main oxidizer valve (MOV) initial ramp was slightly reduced from 60 to 55 % per second to keep the priming sequence of the fuel preburner prime and subsequent main combustion chamber prime on the same relative delta time schedule as in the current start. To prevent stalling of the HPFTP during the start phase, the shaft speed must reach 4600 rpm prior to MCC priming. A current red line check is made at 1.3 seconds to ensure that the HPFTP speed is acceptable for MCC priming. This red line can be shifted approximately 0.2 seconds to reflect the later priming of the MCC. Thus the slower HPFTP speed produces no adverse impact for this altitude start sequence.

The last step to the critical part of the start phase is the priming of the oxidizer preburner. To accommodate the slower ramp of the HPFTP, the oxidizer preburner priming is delayed 0.2 seconds to maintain the proper mixture ratio.

(Annotation continued on the next page).

SSME Upper Stage Use
Altitude Start Analysis (Cont'd)

- Adjustments and Impacts (Cont'd)
  - Main Combustion Chamber (MCC)
    - Prime Occurs 0.24 seconds Later Than Nominal Start
    - Lower HPFTP Shaft Speed Delays Allowable Prime Time
      - MCC Prime Requires Same HPFTP Shaft Speed
  - Fuel Preburner
    - Priming Occurs 0.1 Second Later Than Nominal Start
    - Priming Takes Place at Lower HPFTP Shaft Speed
      - Acceptable
  - High Pressure Fuel Turbopump (HPFTP)
    - Lower Temperature Spike Reduces Hardware Risk to Start Variances
    - Slower Speed Ramp Rate Dictates that 4600 RPM Minimum Speed Redline Can be Delayed ~0.2 seconds to Match Corresponding Component Event Sequence
  - Oxidizer Preburner
    - Priming Occurs 0.2 seconds Later Than Nominal Start

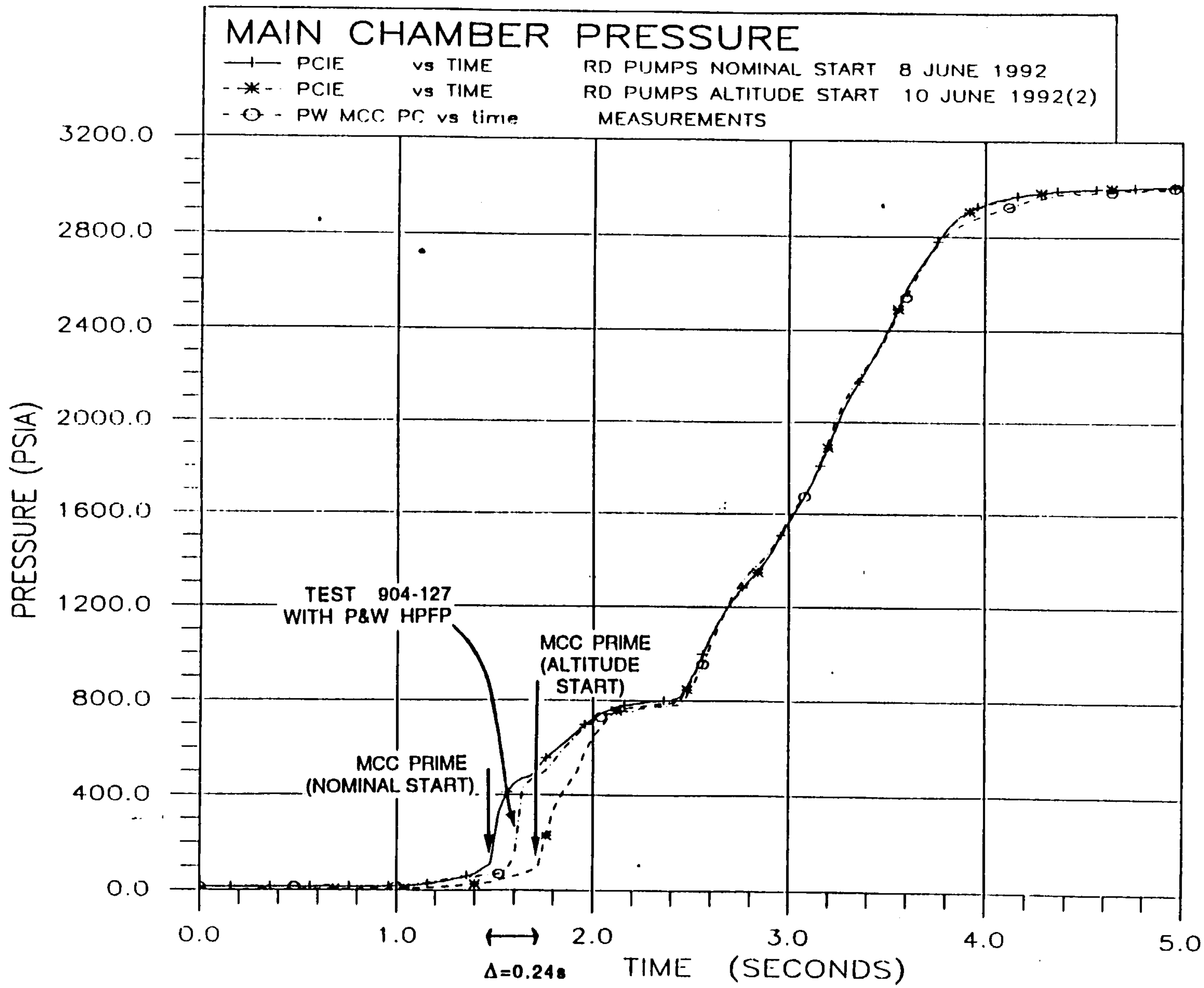
SSME Upper Stage Use
Altitude Start Analysis (Cont'd)

To successfully overcome the breakaway torque and start the two high pressure turbopumps spinning in the start sequence, a burst of propellants must be provided to the preburners early in the sequence. This results in a temperature spike in the high pressure turbopump turbines as is evident in the "Turbine Discharge Temperatures" chart. Currently, the temperature spike on the fuel side is high, occasionally causing minor turbine blade erosion which could be eliminated with a slightly lower temperature spike. The oxidizer side temperature spike is not high enough to cause hardware damage and, in fact, is a benefit as it provides margin in maintaining combustion in the fuel rich propellant mixture. As can be seen in the "Turbine Discharge Temperatures" chart, in establishing the altitude start sequence a 350 degree F lower temperature spike was achieved for the HPFTP turbine and a 200 degree F temperature spike increase was achieved for the HPOTP turbine. These changes provide greater margin for the altitude start case and, more importantly, for the still to be analyzed orbital restart case.

All of the changes required for the altitude start sequence were made in the first 2.4 seconds of the start sequence and are considered highly viable. The remaining altitude start phase of the engine start is almost identical to the current start in speeds, pressures, temperatures, and in duration.

SSME Upper Stage Use

Altitude Start Main Combustion Chamber Pressure



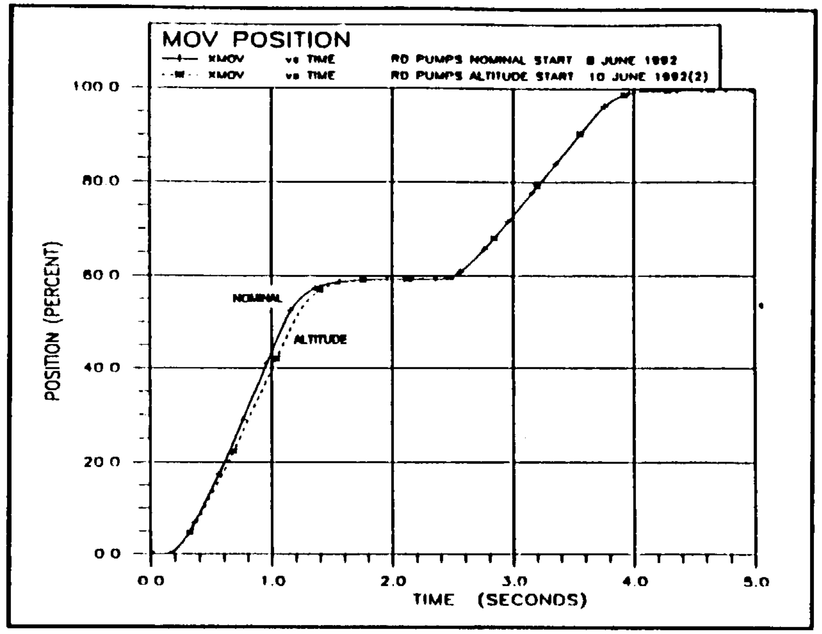
TA3-0132

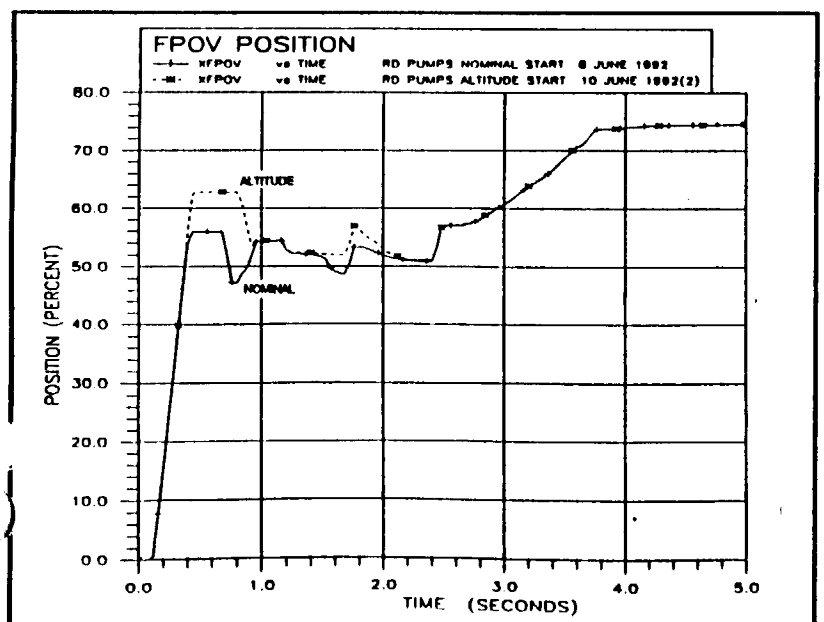
SSME Upper Stage Use

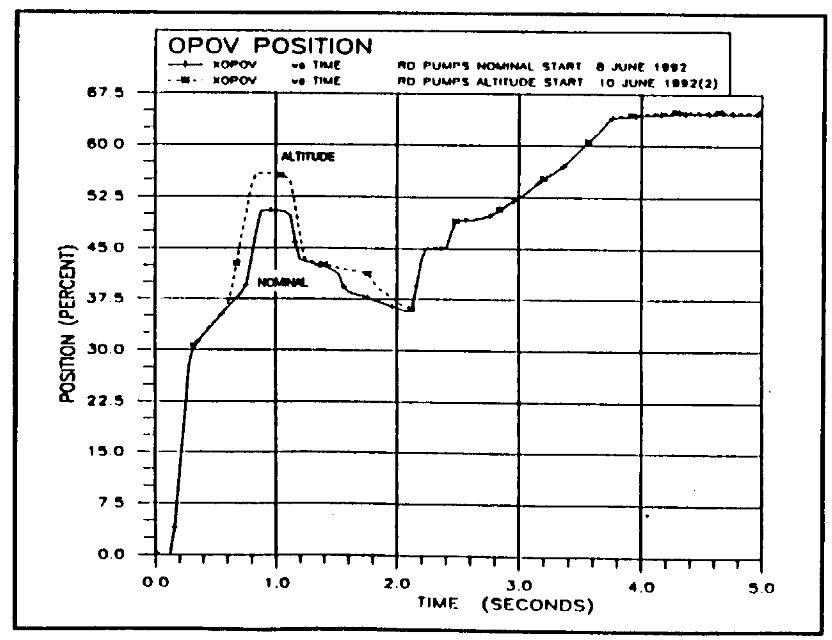
Refer to the previous annotation.

TA3–0132AB

SSME Upper Stage Use
Oxidizer Valve Positions





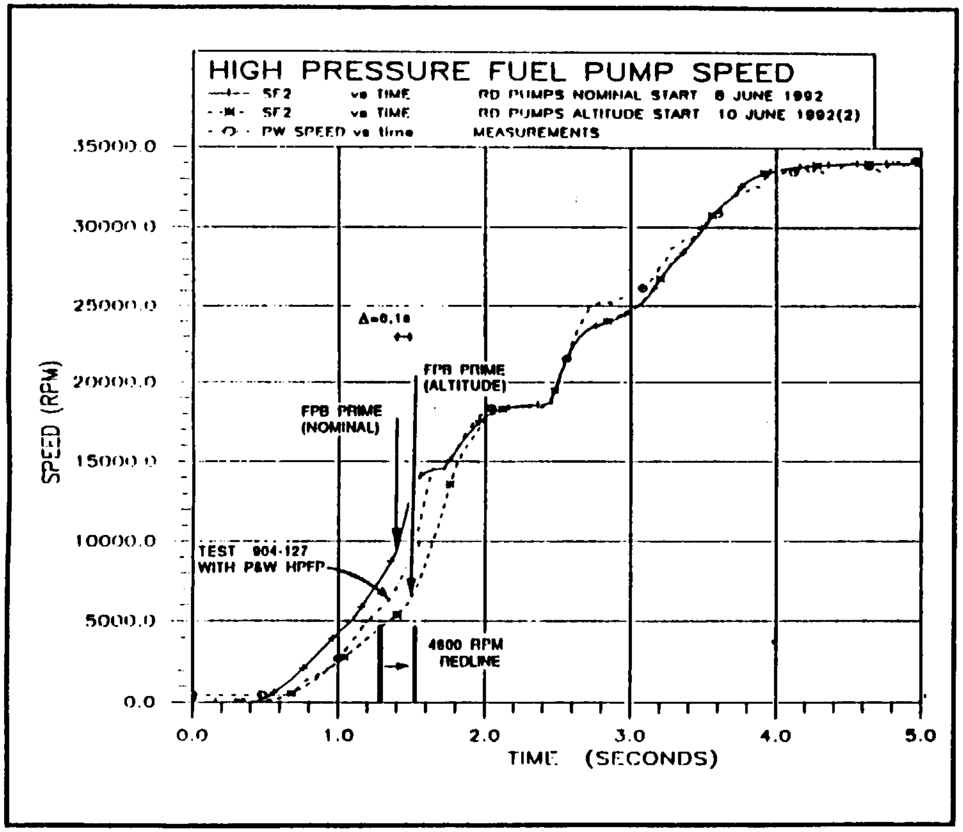


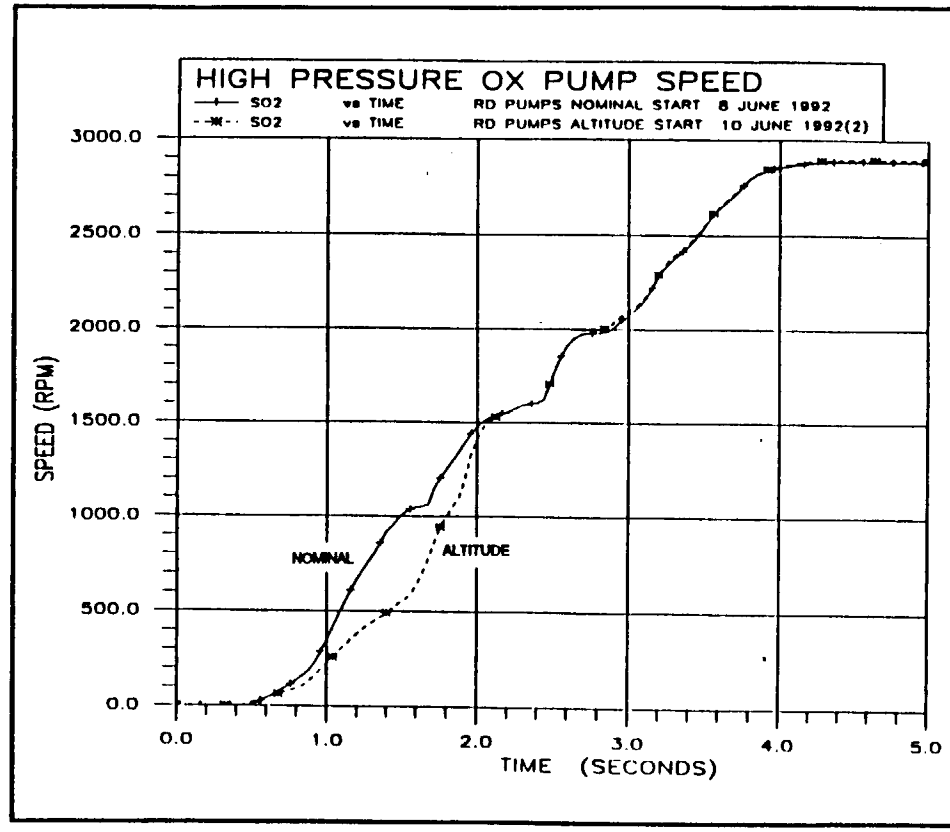
TA3-0130

SSME Upper Stage Use

Refer to the previous annotation.

SSME Upper Stage Use
Turbopump Speeds



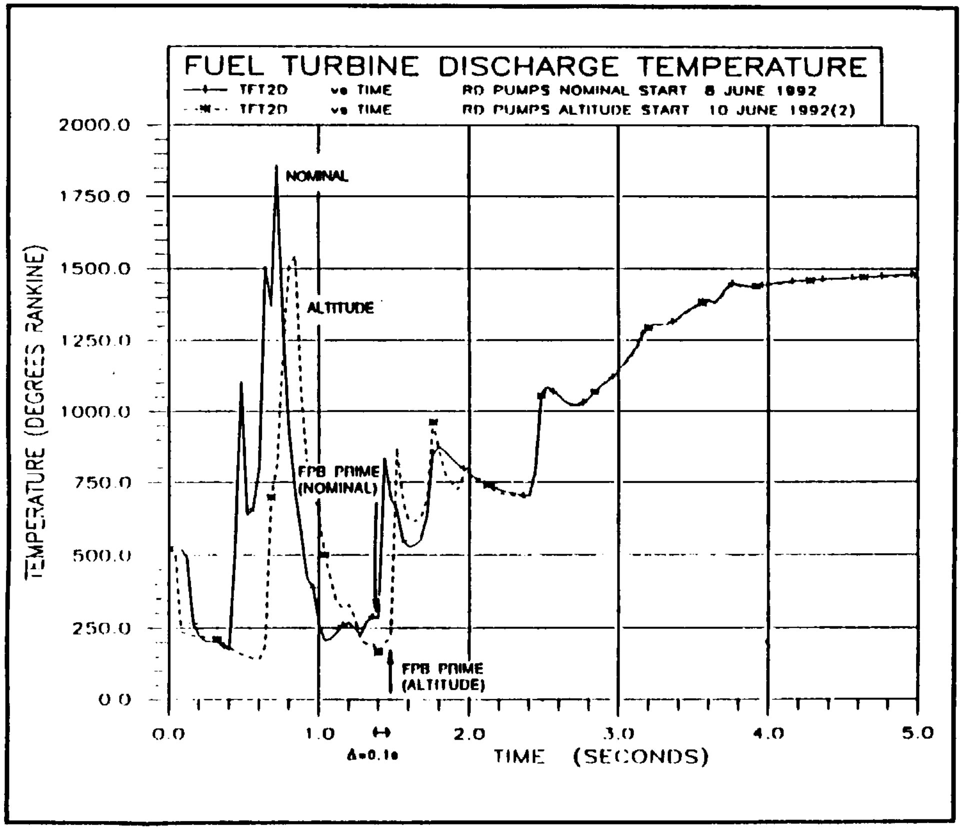


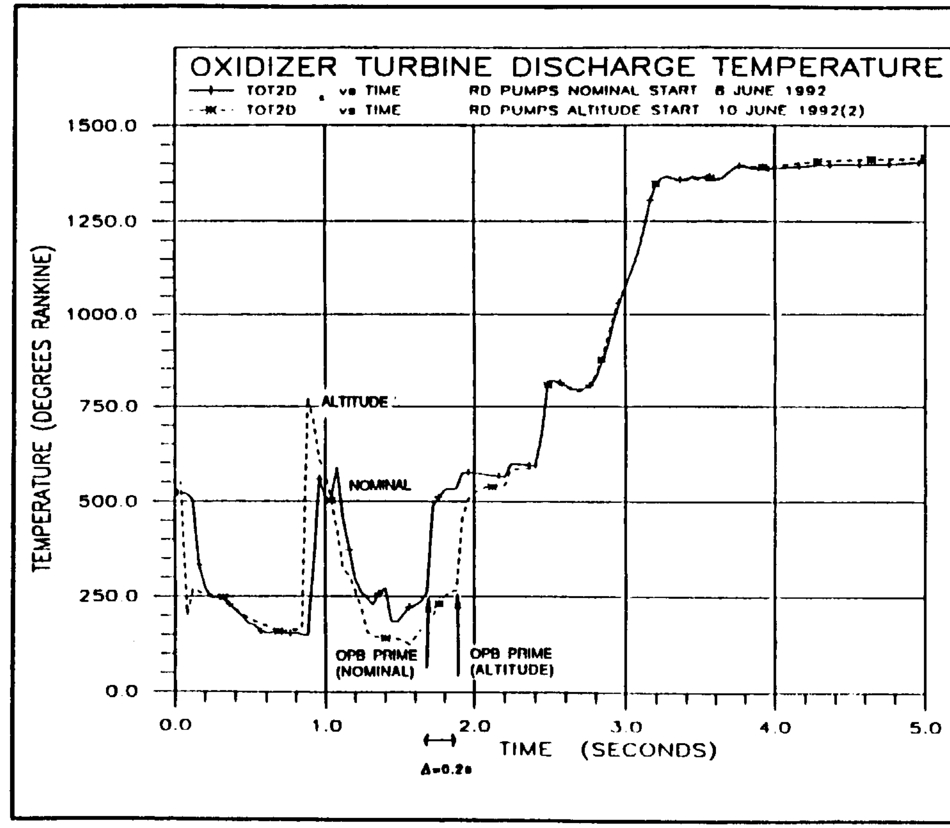
TA3-0131

SSME Upper Stage Use

Refer to the previous annotation.

SSME Upper Stage Use
Turbine Discharge Temperatures





TA3-0129

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SSME Upper Stage Use
Start Assessment

To provide a relative comparison of changes to the start sequence, actual test data from an SSME with the Pratt & Whitney HPFTP was included along with the altitude and nominal start sequences. The comparison shows that the trend is for a slower initial speed buildup, similar to the altitude start characteristics, which is primarily caused by the turbopump rotor having a higher moment of inertia. The limited data available for the Pratt & Whitney HPFTP shows that SSME started successfully using a start sequence modification similar in approach to the altitude start sequence. To date no problems have been encountered with the start sequence used for the Pratt & Whitney HPFTP.

The previous charts have shown that the altitude start initiates its turbopump speed buildup, on both the oxidizer and the fuel sides, later than the current start. Also the main combustion chamber initial pressure ramp occurs later than in the current start. This behavior is similar, but more pronounced, than for the case using the Pratt & Whitney fuel pump. However, by about 2.4 seconds into the start all cases look similar and the bootstrapping of the engine has been successfully completed. The remainder of the start is the same as the current start in all cases.

No change in the philosophy of how the engine is brought up to mainstage was necessary to achieve the altitude start. Various approaches to propellant leads, use of hardware enthalpy, bootstrap operation, and valving only on the oxidizer side all remain the same with only changes in exact valve timings and positions and changes in orificing used to accommodate the lowered inlet pressures characteristic of the altitude start case.

SSME Upper Stage Use
Start Assessment

- Pratt & Whitney Fuel Pump
    - Higher Moment of Inertia
    - Slower Speed Buildup
    - Start Sequence Modified to Achieve Start with No Problems
- Altitude Start
    - Slower Speed Buildup Than with Pratt & Whitney Pump
    - Delta About the Same as Rocketdyne to Pratt & Whitney Fuel Pump Difference
    - Main Chamber Prime Occurs Later But at Same Speed, Flows, Pressures, Temperatures as Current Start
    - No Major Start Philosophy Changes Needed
- Overall Start Time is the Same
    - Current Start, Pratt & Whitney Fuel Pump, Altitude Start

SSME Upper Stage Use
Augmented Spark Igniter Study

With the existing orificing of the supply lines for the ASI's, both altitude start and orbital restart would have significantly lower mixture ratios which would increase risk of ignition failure.

The reorificing solution proposed for upperstage application was derived by mitigating mixture ratio increase at mainstage while retaining ignition/combustion sustaining mixture ratios for ignition. The resulting temperatures during mainstage could potentially cause hardware damage downstream of the two preburners if mixing is not sufficient.

The current transient engine model has limited heat transfer capabilities and therefore may not be accurately depicting the ASI supply line temperature. A custom heat transfer model was built to determine the supply temperatures with higher accuracy so that more refined orificing could be utilized to meet ignition and mainstage mixture ratio requirements.

Preliminary cases were run with the custom heat transfer model for the fuel preburner which had the worst case temperature conditions at mainstage. The results indicate that the original assumptions for flow distribution between the by-pass leg and actual ASI supply line were conservative. The by-pass leg flowrate was found to be higher at mainstage power levels, thereby reducing the temperature of the ASI combustion zone.

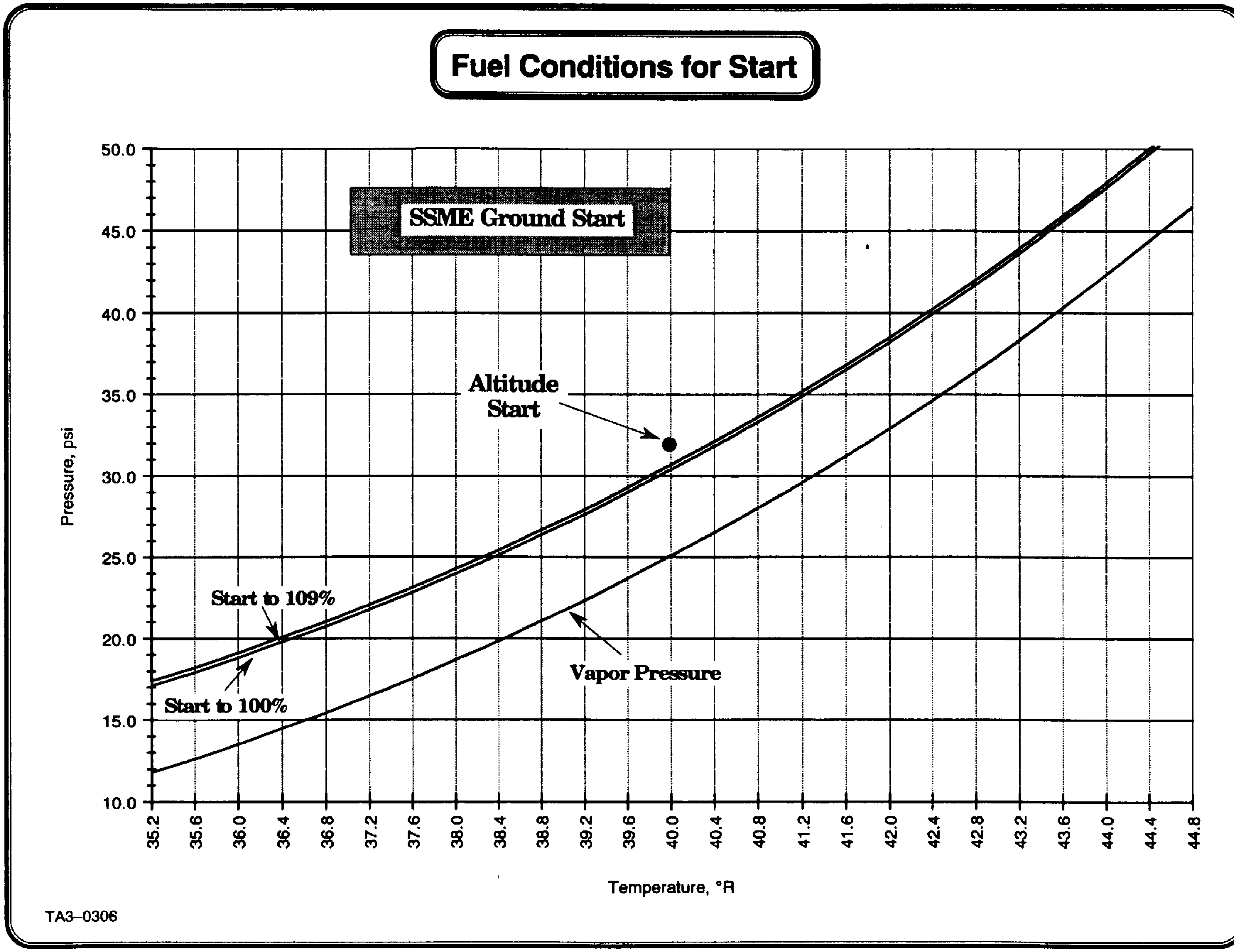
Additional analyses are recommended to further refine the finding and verify ASI operating temperature of the oxidizer preburner ASI combustion zone as well.

SSME Upper Stage Use
Augmented Spark Igniter Study

- Reorificing of ASI LOX supply lines used to more closely approach nominal mixture ratios and propellant volumes during start will result in higher mainstage LOX flowrates at the ASI
    - Higher ASI temperatures
    - Concern that local temperature increase could damage hardware if mixing is not sufficient
- Engine transient model has limited heat transfer modeling capabilities
- Custom heat transfer model was made to simulate flowrates and temperatures accurately for ASI LOX feedlines
    - Cases run show initial assumptions were conservative
        - Therefore temperature increase is less than anticipated
        - However additional analysis and hot fire testing need to verify conditions

SSME Upper Stage Use
Fuel Conditions for Start

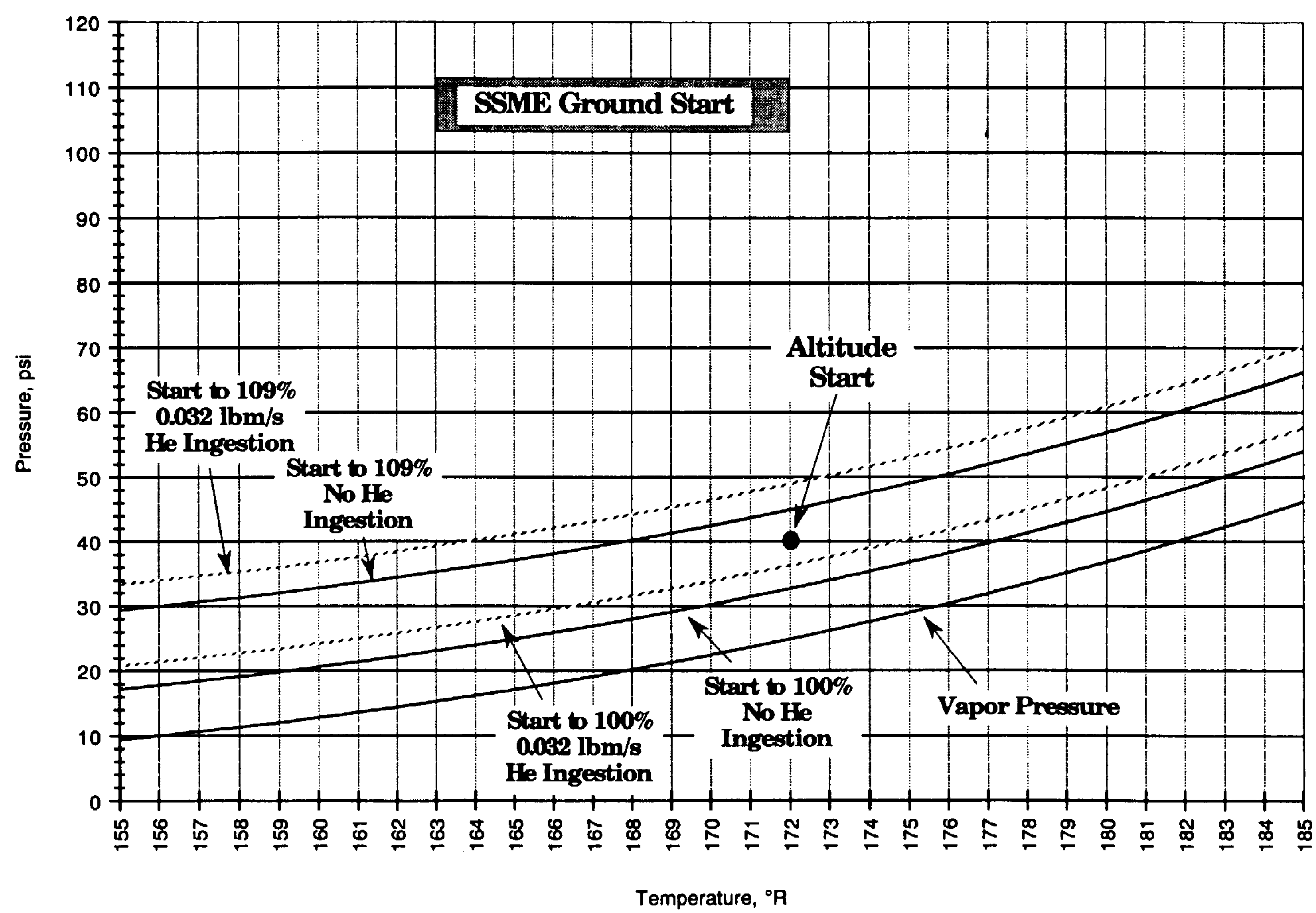
The fuel inlet conditions are improved with the incorporation of thermal control paint and the presence of insulation. The most severe thermal case is when the stage is exposed on the sun side of the Earth. Temperatures even with recirculation approach the NPSP limit for a 109% power level start. With the addition of insulation or of thermal control paint the NPSP margin can be reacquired by reducing the temperature at the inlet.


Fuel Conditions for Start
SSME Ground Start
Altitude Start
Start to 109%
Start to 100%
Vapor Pressure
Pressure, psi
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
35.2
35.6
36.0
36.4
36.8
37.2
37.6
38.0
38.4
38.8
39.2
39.6
40.0
40.4
40.8
41.2
41.6
42.0
42.4
42.8
43.2
43.6
44.0
44.4
44.8
Temperature, °R
TA3–0306

SSME Upper Stage Use
Oxidizer Conditions for Start

The LOX inlet temperatures were influenced more significantly on the solar side of the Earth during coast. Even with recirculation the inlet temperature rose to levels which would be very close to the vapor pressure. Insulation similar to the fuel side insulation was evaluated on the LOX turbopumps and ducting to determine if temperatures could be reduced to acceptable levels. Depending on the insulation absorptance characteristics, the temperatures were found to drop to levels equivalent to the altitude start case. By coating the surfaces with the thermal control paint the temperatures could be reduced below that of the altitude case even on the solar side of the Earth. Even though the temperature was reduced, the start to 109% power level NPSP requirement could not be met. However the start to 100% power level NPSP requirement was satisfied with significant margin. As mentioned earlier for the altitude start case, the engine can be started to 100% power level and then stepped to 109% once sufficient acceleration is established.

Oxidizer Conditions for Start



TA3–0306

SSME Upper Stage Use
Altitude Start Conclusions

The primary difference between the operating conditions for the current start versus the altitude start is a lower set of pump inlet pressures. The analysis performed has shown that an altitude start is feasible with the SSME engine with only modifications to valve sequencing (both as to position and timing) and some reorificing, at least with inlet pressures of 32 psia on the fuel side and 40 psia on the oxidizer side.

The net effect of these lowered pressures is to delay the initial bootstrap rate, although the overall time to bootstrap the engine and the time to full mainstage remains the same as the current start.

SSME Upper Stage Use
Altitude Start Conclusions

- Altitude Start of SSME is Feasible
  - Preburner Valves Sequenced to Higher Positions and Modified Timings to Accommodate Lower Inlet Pressure
    - Modifies Basic Open Loop Control
  - Closed Loop Control Converges
  - Initial Bootstrap Rate Reduced From Current Start
  - Time to Reach Mainstage Not Affected
- Pressures
  - LOX – 40 psi
  - H_2 – 32 psi

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Orbital Restart

TA3-0273

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Orbital Coast Phase Thermal Analysis

SSME Upper Stage Use
Orbital Coast Phase Thermal Analysis

To minimize cost and lead time, the approach chosen for the orbital coast phase thermal analysis was to use an existing thermal mass model of the SSME with modifications and upgrades to predict engine component thermal data critical to the start sequence. This approach provided a first order analysis of the engine component thermal characteristics which can be inserted into the existing transient start model of the SSME.

Predicted data for the Space Station Freedom was utilized for the basic orbital/environment conditions. Assuming that limited control of temperatures during the orbital coast phase is achievable, a key analysis goal was to determine if temperatures similar to those in the altitude start would occur during the orbital coast phase. This would allow a common start sequence which in turn would minimize engine development cost. Vehicle operations data and thermal data from the Apollo SIV-B stage was utilized for defining stage orientation conditions and for performing a check on the results.

SSME Upper Stage Use
Orbital Coast Phase Thermal Analysis

- Approach
  - Modify Existing SSME Thermal Mass Model To Provide Thermal Data On Components Critical To Start Sequence
  - Utilize Space Station Freedom/J-2 (Apollo SIV-B Stage) Orbital Environment Predictions/Data To Baseline Orbital Environment For A SSME On An Upper Stage
- Goals
  - Maintain Common Start Sequence For Altitude Start And Orbital Restart If Feasible (Valve Schedules, Component Temperature Requirements, Priming Sequence)
  - Minimize Need For Required Hardware Changes
  - Minimize Stage Impact

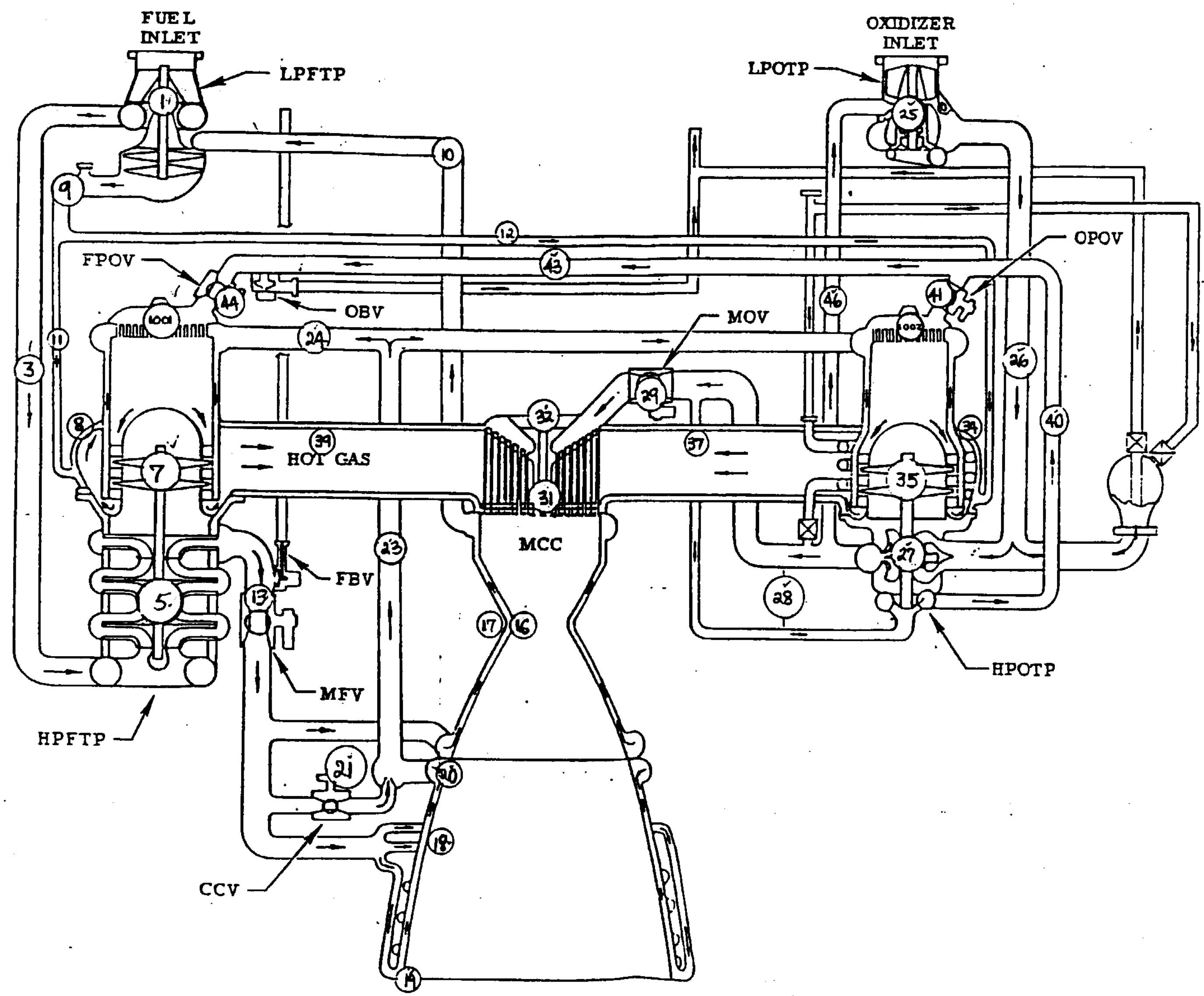
SSME Upper Stage Use

Thermal Mass Model Node Map

The thermal model used for predicting the component temperatures utilizes a node structure which typically corresponds with the gross component structure of the engine. The model consists of 35 nodes that describe the key features of the cryogenic propellant feed systems and the hot gas system. Components that have a cryogenic and a hot gas section are generally split, having separate nodes for the cold and hot sections. Larger components, such as the nozzle, have been given additional nodes to provide added detail where significant temperature variations may exist.

The chart on the facing page shows where each numbered node is located and is useful for interpreting the temperature versus time curves for various components shown later.

SSME Upper Stage Use
Thermal Mass Model Node Map



TA3-0176

SSME Upper Stage Use
Orbital Thermal Analysis

More than one source of radiation influences the temperature of the engine components in orbit. The main source is the sun which provides radiation directly and by radiation reflected by the earth's surface back towards space in what is known as Earth albedo. Approximately one-third of the incident radiation from the sun is reflected back to space in Earth albedo. In addition, earth emits radiation as a black body and this radiation is present on the sub-solar and solar sides of the earth. This combination of radiation sources coupled with the orbit path of the stage around the earth produces a periodic intensity of the total radiation which the stage and engine experience while in orbit.

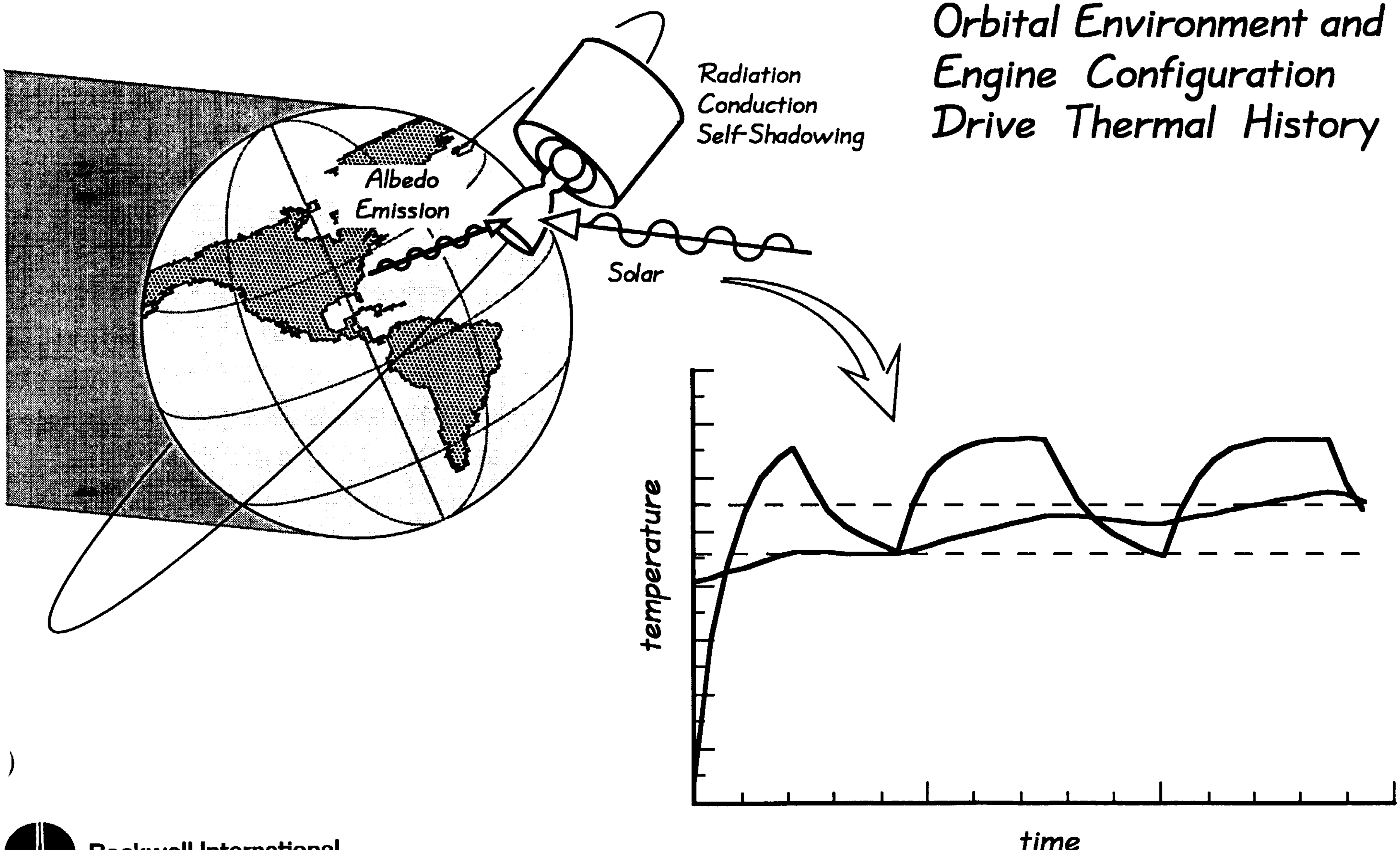
During orbit, the stage is rotated about its major axis; thus, the stage is exposed to the sun 50 percent of the time and to the Earth's surface 50 percent of the time on the solar side. On the sub-solar side, the stage receives less energy: earth's black body emission 50 percent of the time and space background radiation 50 percent of the time.

The components themselves radiate energy to each other and to space. Conduction also occurs between components. Lastly, some components shadow other components from some of the incident energy. The net effect is a complex thermal history which varies among different components.

As shown, the temperature history of certain components will set minimum times for restart either by reaching needed limits or through thermal conditioning. Temperature may also exceed limits after a time either imposing a maximum time for restart or, more likely, a requirement for conditioning or other thermal control.

TA3–0223A

SSME Upper Stage Use
Orbital Thermal Analysis



Orbital Environment and Engine Configuration Drive Thermal History

SSME Upper Stage Use
Thermal Analysis

The basic thermal mass model utilized for the study assumes that components have ideal thermal properties for radiation collection. To provide realism and conservatism, adjustments were evaluated and made to the model to account for the non-ideal thermal characteristics of the engine system. The evaluation showed that reducing the radiation surface area has the greatest influence on component temperature rise. The surface areas for the components are typically cylindrical or have cross sections which reduce the available surface area. In addition, the engine assembly has close component spacing which blocks surfaces of adjacent components. Through a sensitivity study using the SIV-B J-2 engine temperature data for comparison, estimates were made for the reduction needed for realistic simulation. The result was a 50 percent reduction which was used for subsequent analysis.

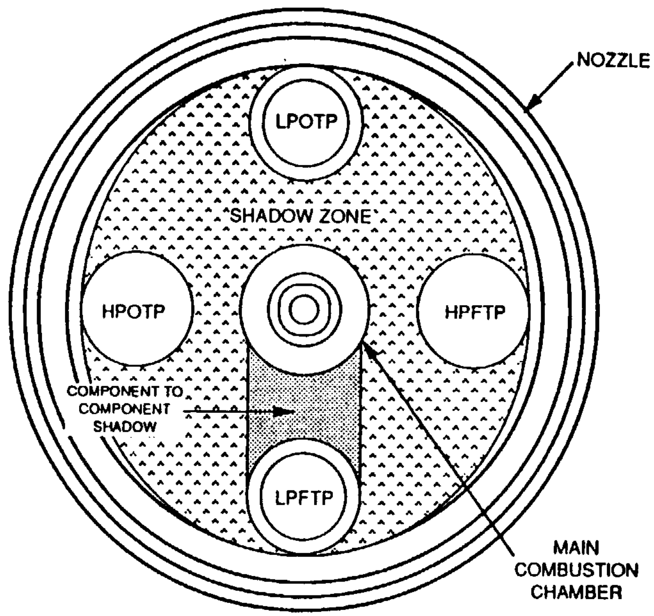
SSME Upper Stage Use
Thermal Analysis

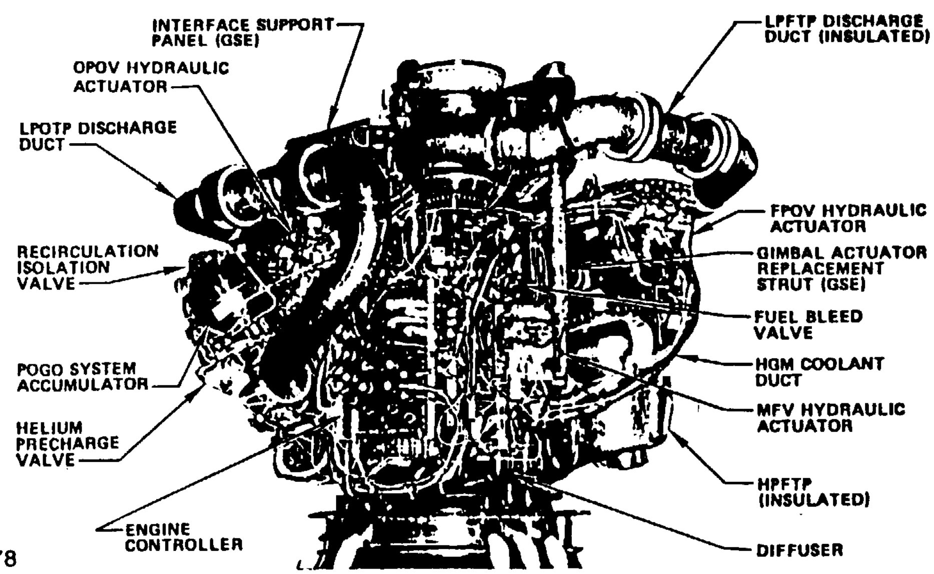
- Treatment Of Solar Irradiance, Earth Albedo, And Earth Emmissivity Has Greatest Influence On Component Heating Rate
  - Component Surfaces Not “Ideal” For Radiation Collecting
    - Ducting, Lines, Subcomponents And Other Major Components Block Radiation To Major Components Surfaces
    - Major Component Surfaces Are Typically Circular - Not "Ideal"Flat Plate Collectors
    - Estimated Reduction Of Radiation Surface Area Is 50% To Major Component Surfaces (40% For Shape And 10% For Blockage) For Realistic Simulation

SSME Upper Stage Use
Component Shadowing

Packaging of the SSME was accomplished with the goal of minimizing needed space for the engine system. In meeting that goal component spacing is very dense on the SSME and blockage of radiation to components occurs frequently. Major components are clustered around the centerline of the engine with the main combustion chamber and nozzle along the centerline. Ducting connecting the major components typically wrap around the engine outboard of the major components creating a shadowing of the major components which in turn shadow the main combustion chamber. The nozzle does not experience shadowing to the same extent as the other components, however, the 50 percent surface area reduction was also applied to the nozzle as a conservative measure for the thermal analysis .

SSME Upper Stage Use
Component Shadowing





TA3-0178

Component Shadowing Region

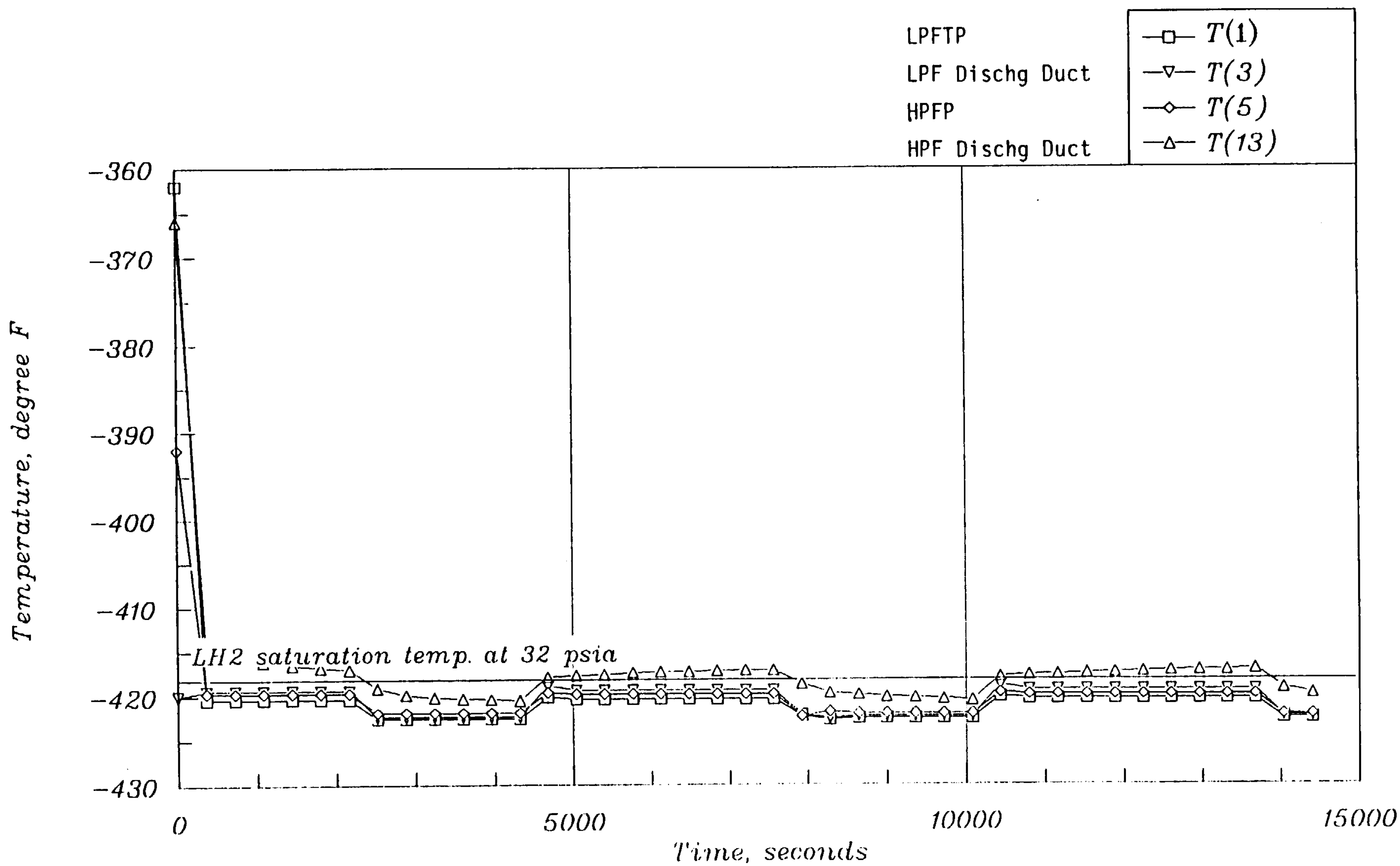
- Contains Ducting, lines, subcomponents and Harnesses which Block Solar Irradiance to Major Component Surfaces
- Major Components Have Surfaces which Face Toward the Centerline of the Engine which Experience Shadowing from Other Major Components
- Estimated Reduction of Solar Irradiance is 50% to Major Component Surfaces Except for the Nozzle Section of the Engine

SSME Upper Stage Use
Thermal Modeling Results

This plot is from one of the later modeling cases run in which the minimum recirculation needed to precondition the turbopumps was determined. The temperatures shown are for the low pressure and high pressure liquid hydrogen pumps and the interconnecting ducting. The temperatures are brought down to give adequate NPSH margin for the two pumps and the low pressure pump discharge duct that runs between the pumps. The high pressure pump discharge duct is downstream of the pumps and does not affect NPSH margin. The minimum desired temperature is approximately four degrees cooler than the saturation temperature at 32 psia. This condition was found to be satisfied with a recirculation flowrate of one pound per second through the fuel system. This flowrate is within the pumping capabilities of the current recirculation system used on the SSME today which nominally pumps at 1.5 pounds per second for the engine start prechill used on the Space Shuttle.

A periodic temperature fluctuation of approximately three degrees occurs due to the shift in input radiation that corresponds to the solar and shadow sides of the earth during orbit.

SSME TMM HEAT SOAKBACK CASE 16
LH2 re-circulation flow = 1. lbm/sec. LOX re-circulation flow = 1. lbm/sec.
Solar heating = 429 btu/ft2-hr. Half of the surface area



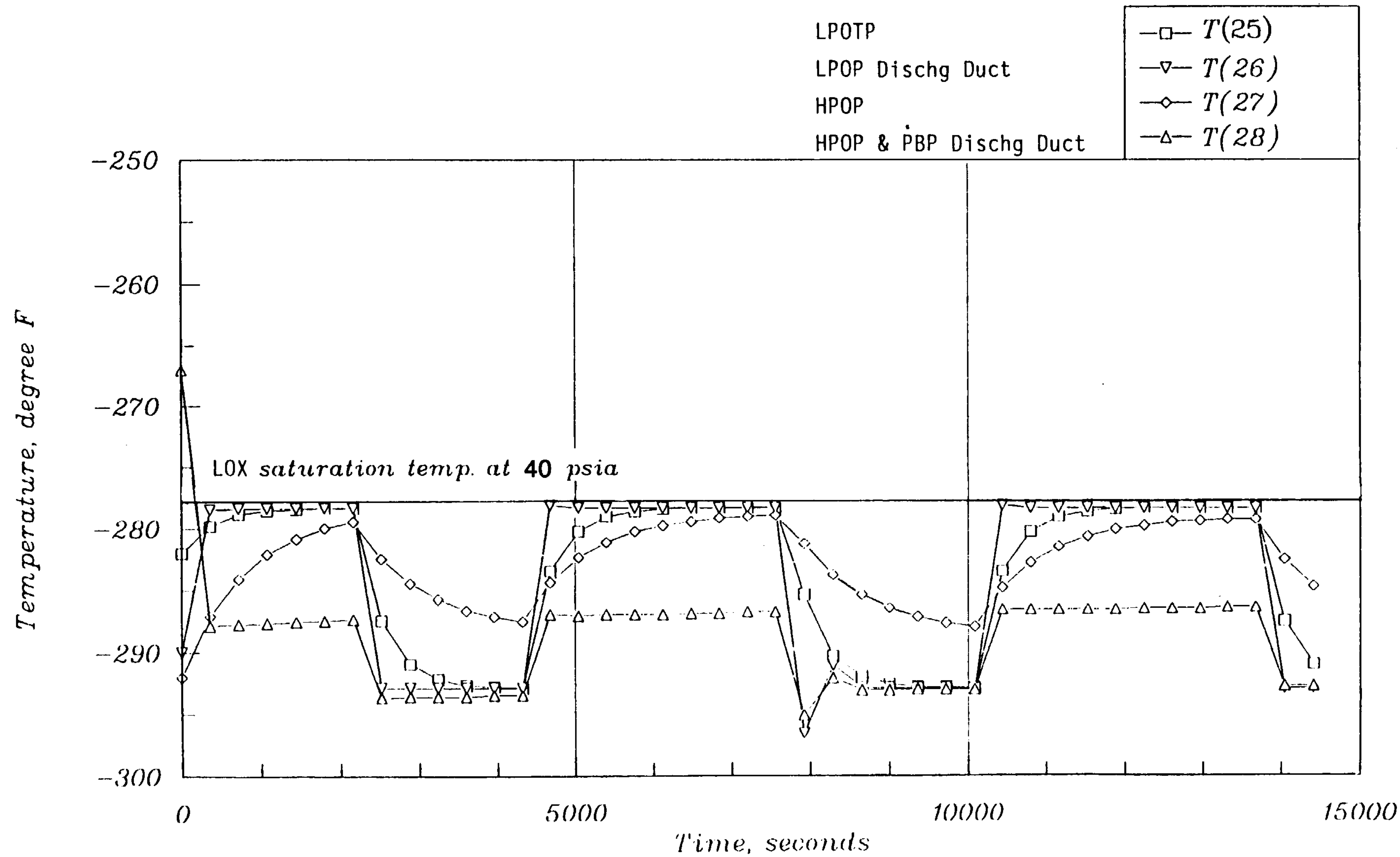
SSME Upper Stage Use
Thermal Modeling Results

This plot shows the LOX turbopump system for the same case as the previous chart. Temperature fluctuation is greater due the thermal properties of the LOX. Sufficient NPSH margin can be maintained when the stage is on the shadow side of the Earth. However, the temperature rise that occurs when the stage is on the solar side reduces the NPSH margin below adequate levels for starting the engine. A later plot will show how this problem is solved. The recirculation flowrate utilized for this case was one pound per second for the LOX system which is substantially less than the four and a half pound per second prechill bleed flowrate used for the Space Shuttle today.

SSME TMM HEAT SOAKBACK CASE 16

LH2 re-circulation flow = 1. lbm/sec. LOX re-circulation flow = 1. lbm/sec.

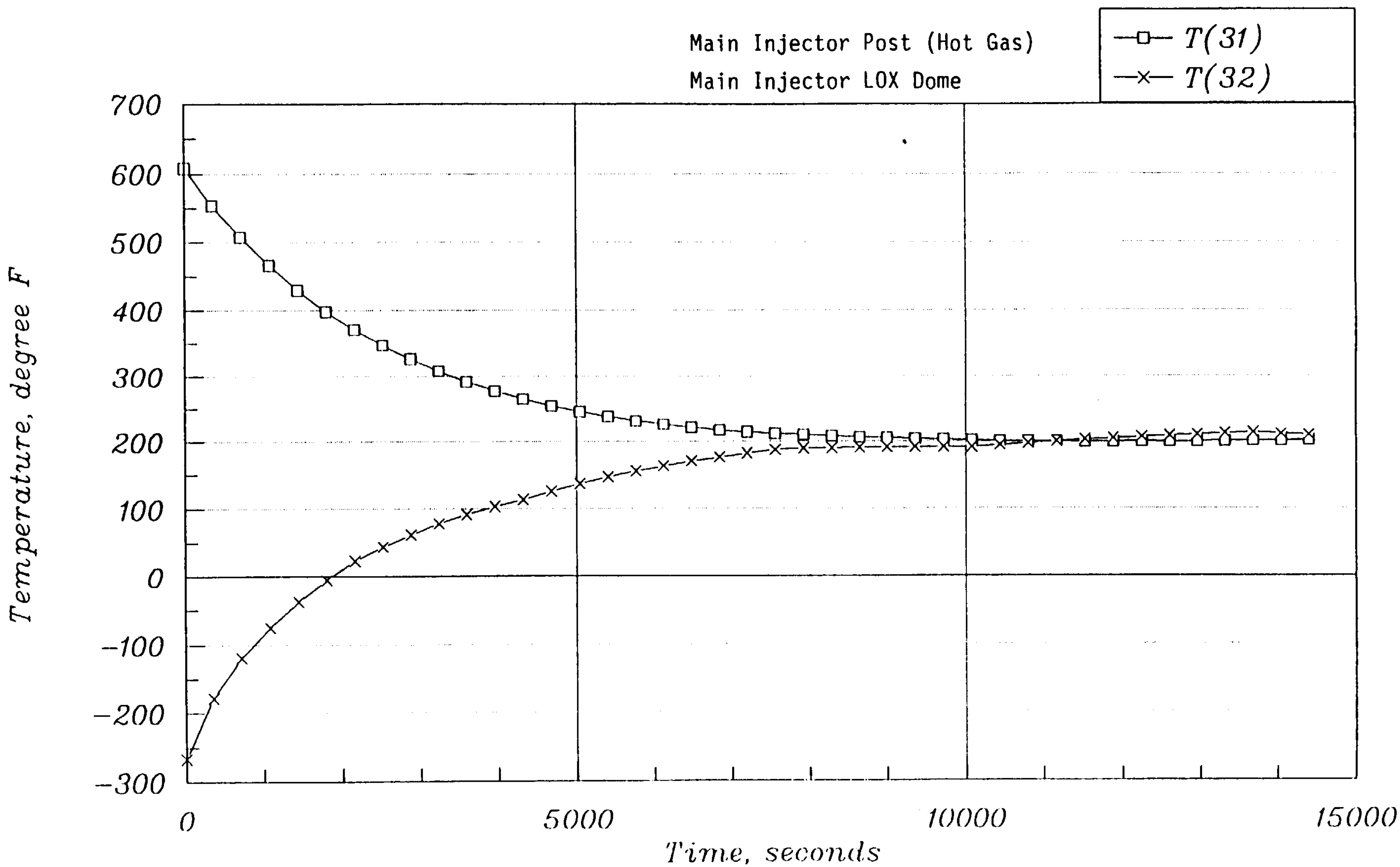
Solar heating = 429 btu/ft2-hr. Half of the surface area



SSME Upper Stage Use
Thermal Modeling Results

This chart shows the main injector temperature trend for the same case as the previous chart. Both the cold LOX dome which feeds into the injector posts and the hot gas section equalizing during the coast period with the dome section reaching ambient temperature in approximately twenty two hundred seconds.

SSME TMM HEAT SOAKBACK CASE 16
LH2 re-circulation flow = 1. lbm/sec LOX re-circulation flow = 1. lbm/sec
Solar heating = 429 btu/ft2-hr half of the surface area

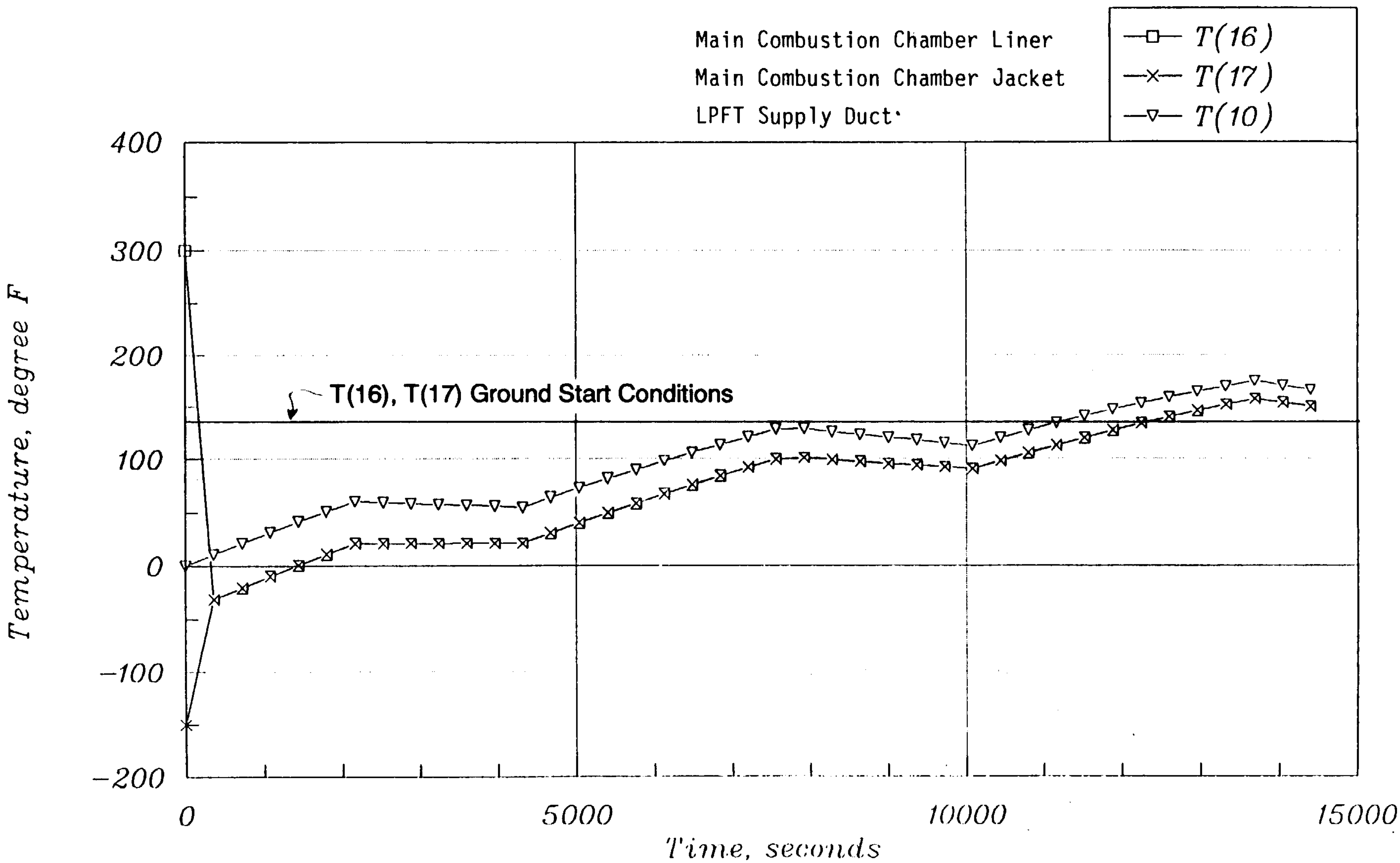


SSME Upper Stage Use
Thermal Modeling Results

This chart shows the main combustion chamber liner (hot) and jacket (cold) structures equalizing along with the duct which feeds the low pressure fuel turbine with MCC coolant. The temperatures reach ambient conditions in approximately two thousand seconds.

TA3-0241A

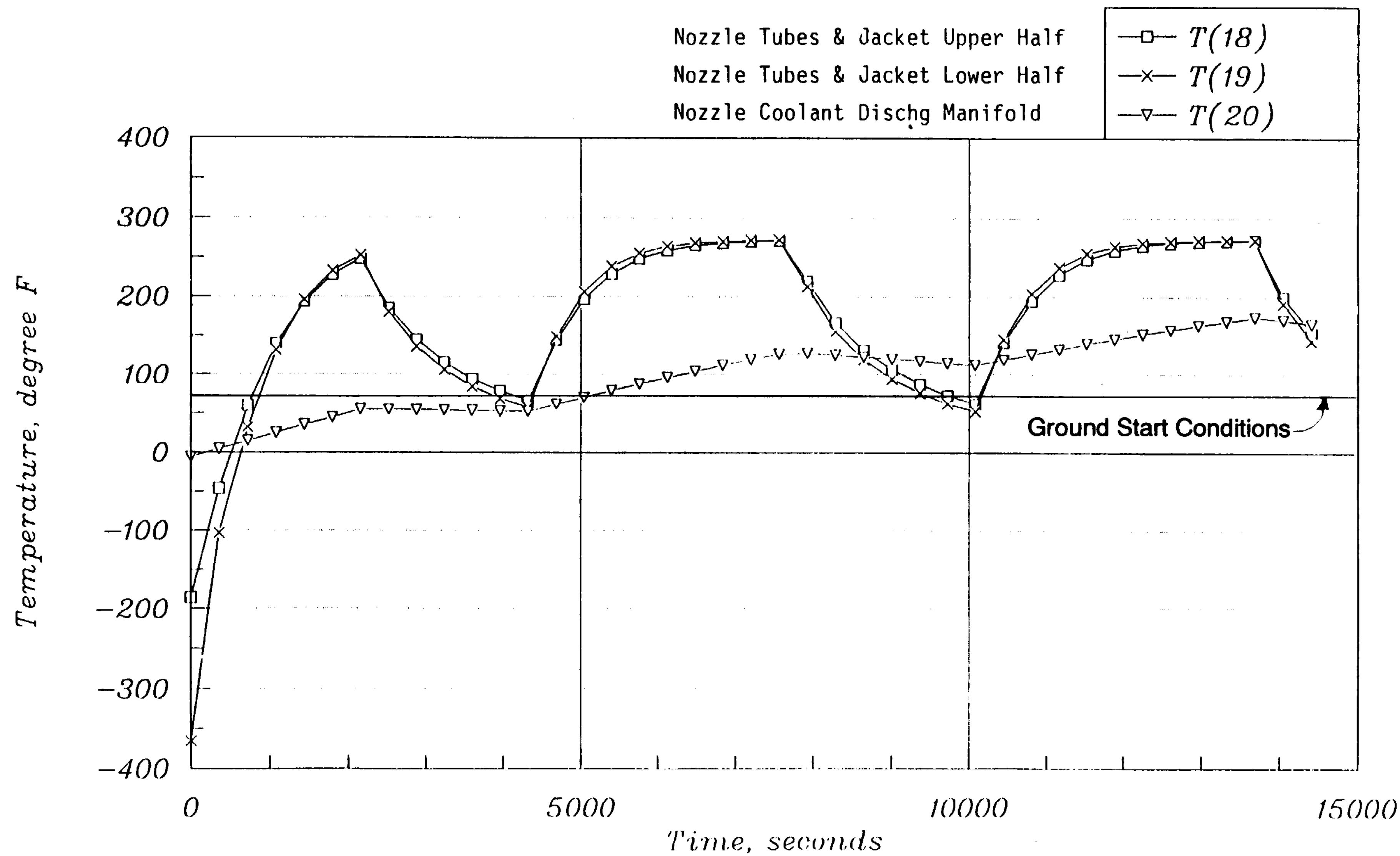
SSME TMM HEAT SOAKBACK CASE 16
LH2 re-circulation flow = 1. lbm/sec LOX re-circulation flow = 1. lbm/sec
Solar heating = 429 btu/ft2-hr half of the surface area



SSME Upper Stage Use
Thermal Modeling Results

This chart shows the nozzle temperatures for the tubes and jacket structure along with the coolant discharge manifold. All of them trend upward in a cyclic fashion. The tubes and jacket have a very large surface area in relation to their mass. Thus the amplitude of their temperature swings is much greater than that of the manifold for the cycling which occurs between the solar and shadow sides of the earth. Temperatures rise rapidly for the nozzle due to its structure. Ambient conditions are reached in approximately eleven hundred seconds.

SSME TMM HEAT SOAKBACK CASE 16
LH2 re–circulation flow = 1. lbm/sec LOX re–circulation flow = 1. lbm/sec
Solar heating = 429 btu/ft2–hr half of the surface area

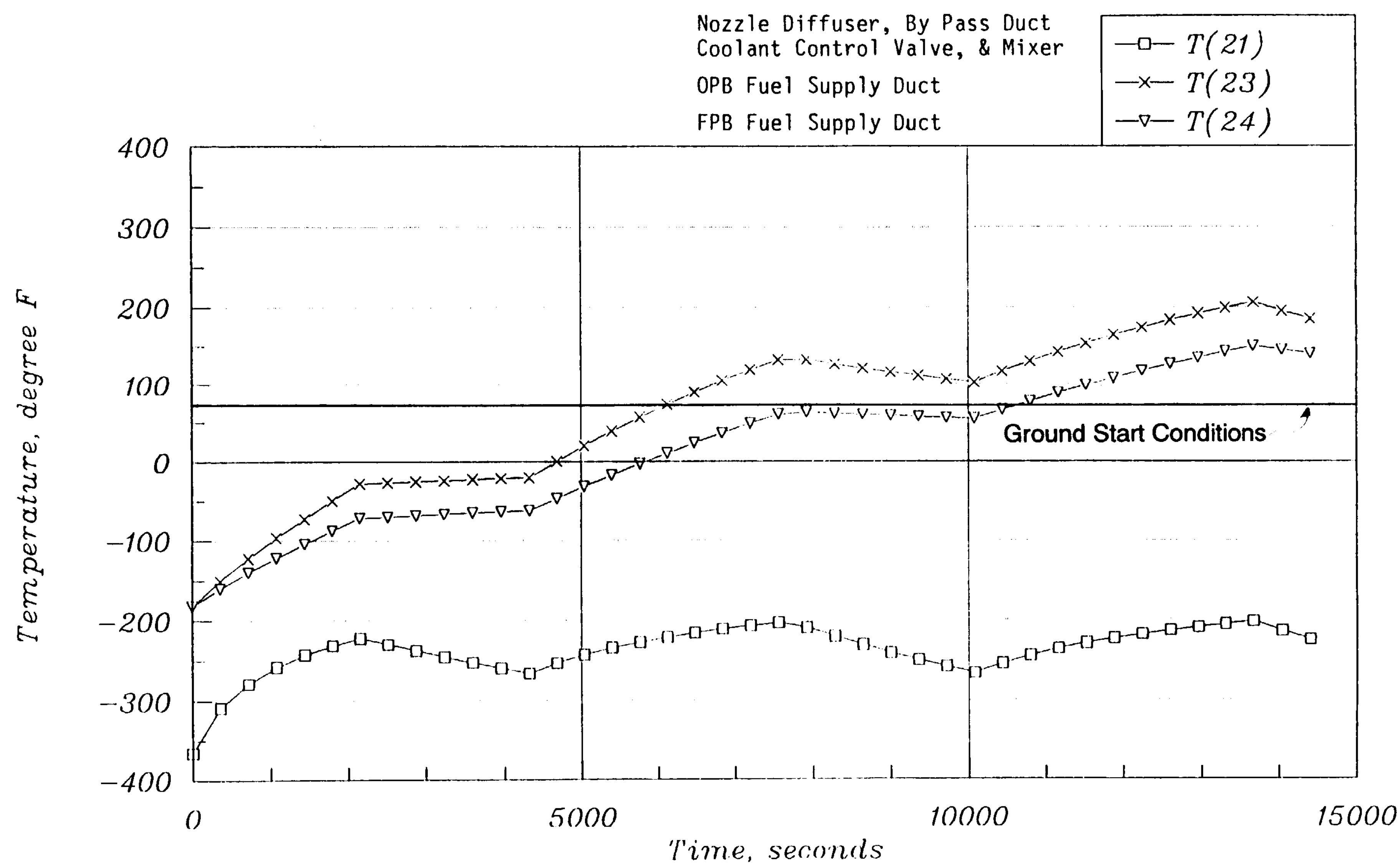


SSME Upper Stage Use
Thermal Modeling Results

This plot shows the network components which route the hydrogen to the preburners from the nozzle coolant circuit. The diffuser which routes the hydrogen to the nozzle feedlines and to the by-pass circuit (coolant control valve) along with the mixer which recombines the hydrogen has a slow temperature response and never reaches ambient since the surface area is small. These components are not expected to have a major influence on the start sequence. However, if the restart analysis shows that problems may exist, then further detailed modeling would be required to quantify the impact. Also, as was shown earlier, because the nozzle temperature is higher than ambient, it will offset the lower nozzle diffuser temperature.

The other two temperatures shown are the preburner fuel supply ducting which warms to ambient in approximately 5200 seconds for the oxidizer preburner and 6200 seconds for the fuel preburner. Again the lower temperature rise is expected to be offset by the hot nozzle temperatures.

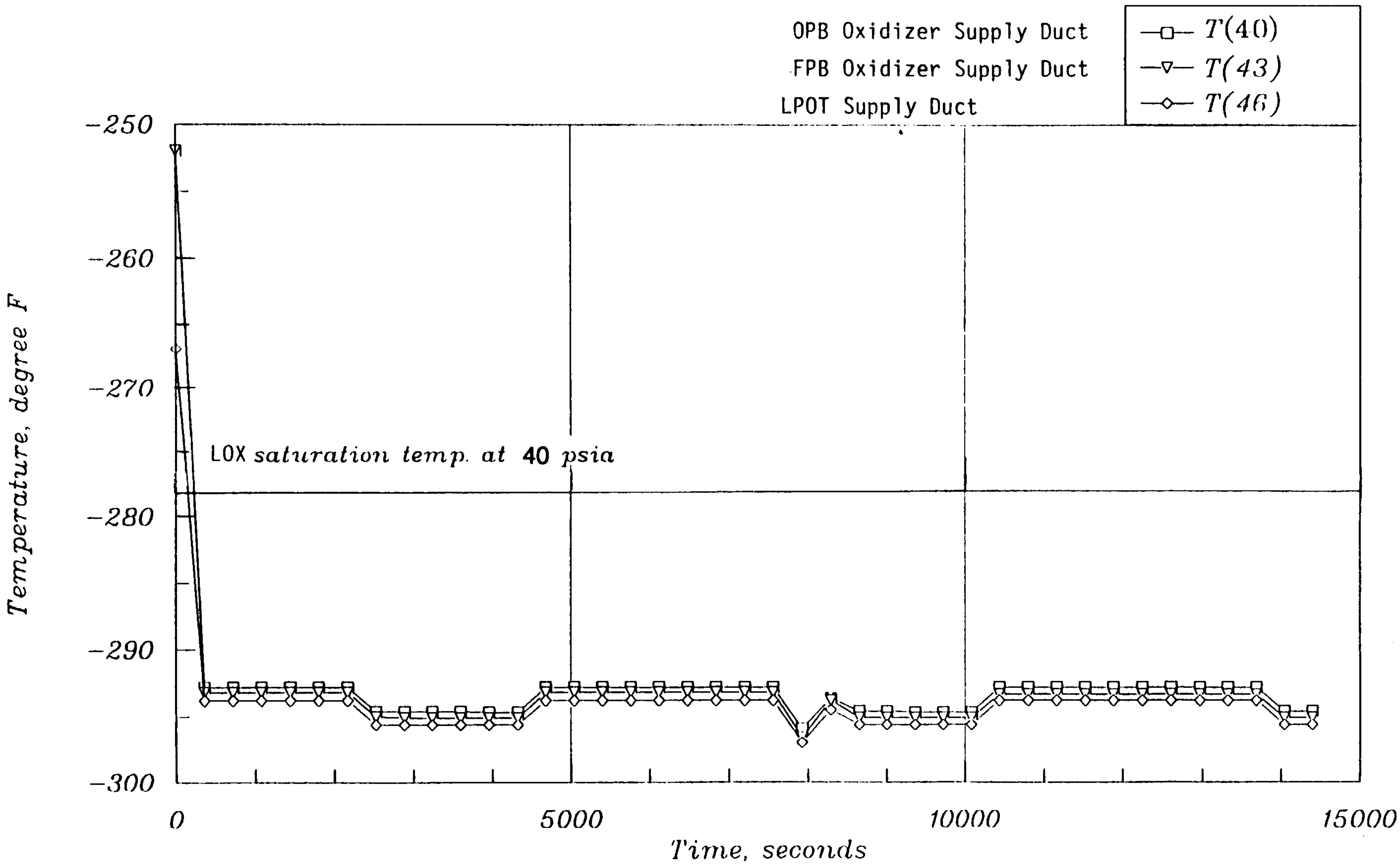
SSME TMM HEAT SOAKBACK CASE 16
LH2 re-circulation flow = 1. lbm/sec LOX re-circulation flow = 1. lbm/sec
Solar heating = 429 btu/ft2-hr half of the surface area



SSME Upper Stage Use
Thermal Modeling Results

This chart shows the temperatures of the ducting which routes the LOX to the preburners from the preburner pump and the duct which supplies LOX to drive the low pressure oxidizer turbopump. All of these ducts are influenced by the recirculation flow of oxidizer through the LOX turbopump system as can be seen by the chilling trend and cold temperatures. The chilling bleed flow that exists today on the SSME may not fully chill the preburner feedlines. This difference in temperature could potentially affect the start sequence in which case additional detailed thermal modeling may be required to assess the impacts. The restart analysis results should determine if the preburner supply line temperatures influence the start sequence significantly.

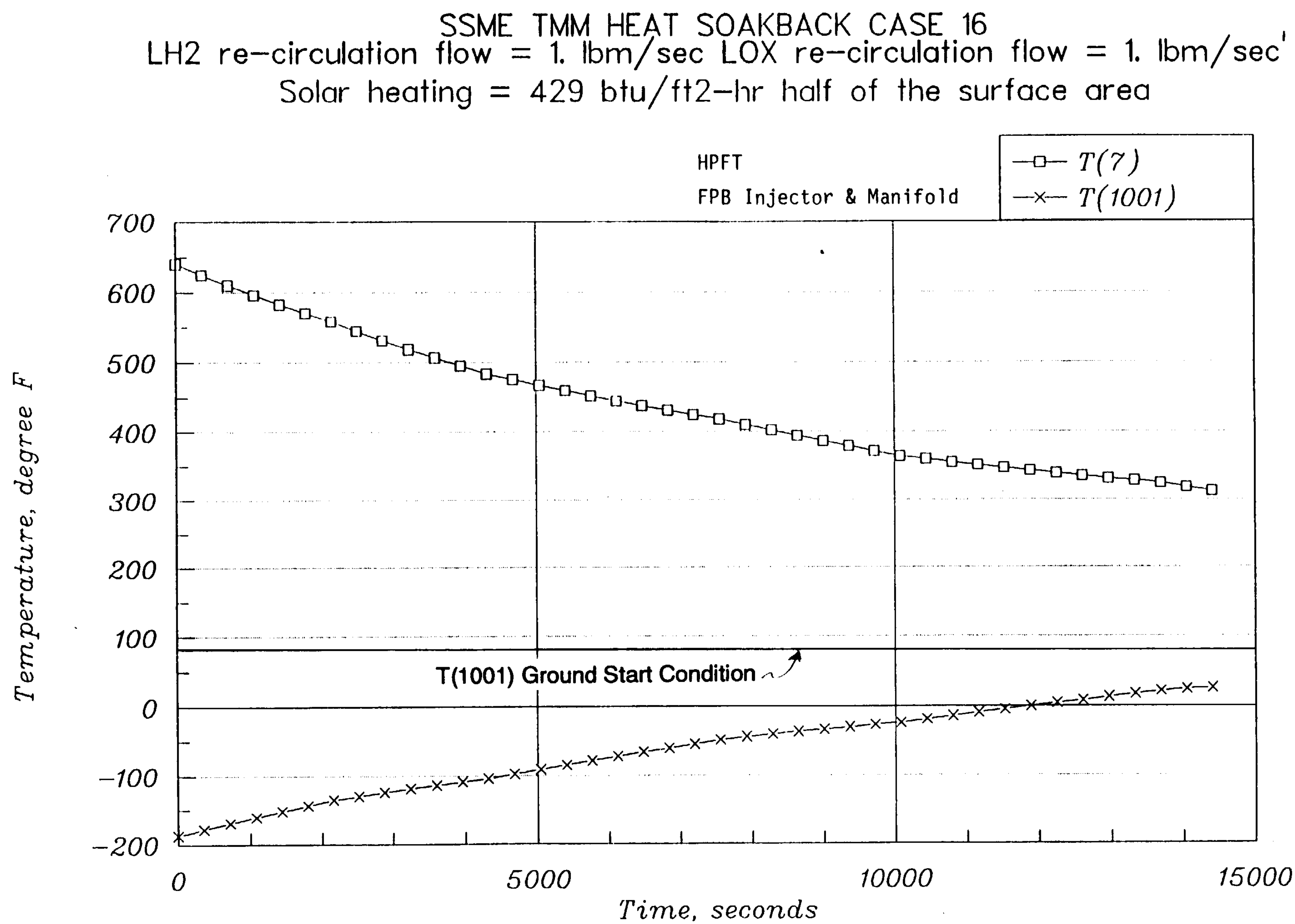
SSME TMM HEAT SOAKBACK CASE 16
LH2 re-circulation flow = 1. lbm/sec. LOX re-circulation flow = 1. lbm/sec. 1
Solar heating = 429 btu/ft2-hr. Half of the surface area



SSME Upper Stage Use
Thermal Modeling Results

This chart shows the high pressure fuel turbopump turbine and preburner temperatures gradually approaching each other. The turbine temperature slowly drops from above six hundred degrees to a little above three hundred after four hours. This temperature regime is high enough to prevent moisture from remaining in the turbine section during the first cutoff and forming into ice. Any water present at cutoff will vaporize an be forced from the turbine and preburner by the shutdown purges.

The preburner LOX dome and gas injector manifold were grouped together as one temperature node. The temperature rise is slow and does not reach ambient until approximately thirteen thousand seconds after cutoff. This slow response is due to the small surface area of the preburner. The temperature at the one hour time frame is below the ambient regime, however, this is offset by the higher nozzle temperatures upstream of the preburners. If the restart model shows the preburner temperature to be a driver for restarting the engine, higher temperatures could be achieved by having a longer cutoff purge to warm the preburner.

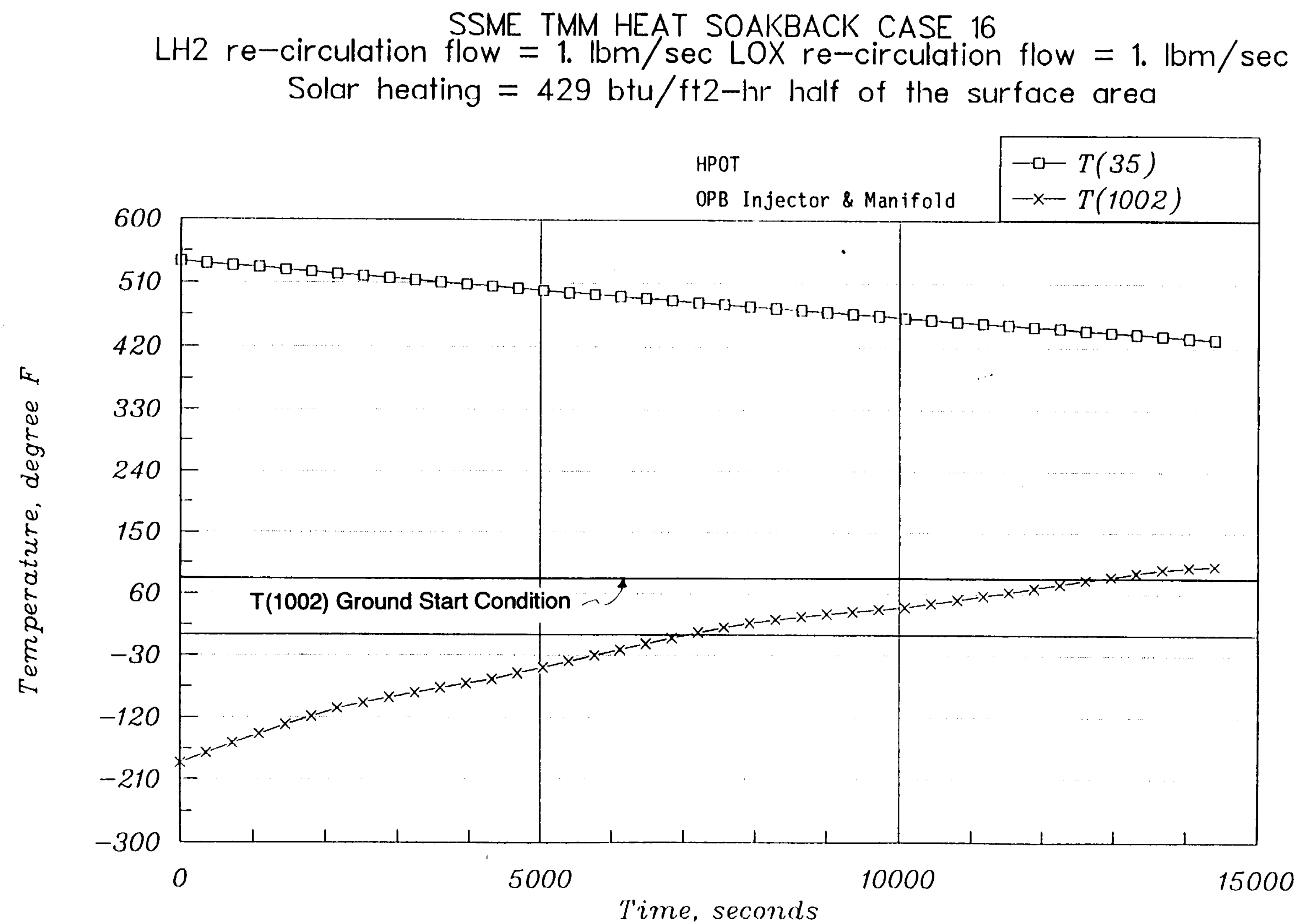


SSME TMM HEAT SOAKBACK CASE 16
LH2 re-circulation flow = 1. lbm/sec LOX re-circulation flow = 1. lbm/sec
Solar heating = 429 btu/ft2-hr half of the surface area
HPFT
FPB Injector & Manifold
T(7)
T(1001)
T(1001) Ground Start Condition
Temperature, degree F
Time, seconds
700
600
500
400
300
200
100
0
−100
−200
0
5000
10000
15000

SSME Upper Stage Use
Thermal Modeling Results

This chart shows the high pressure oxidizer turbopump turbine and preburner temperatures gradually approaching each other. The turbine temperature slowly drops from above five hundred degrees to a little above four hundred twenty degrees after four hours. This temperature regime is high enough to prevent moisture from remaining in the turbine section during the first cutoff and forming into ice. Any water present at cutoff will vaporize an be forced from the turbine and preburner by the shutdown purges.

The preburner LOX dome and gas injector manifold were grouped together as one temperature node. The temperature rise is slow and does not reach ambient until approximately seventy five hundred seconds after cutoff. This slow response is due to the small surface area of the preburner. The temperature at the one hour time frame is below the ambient regime, however, this is offset by the higher nozzle temperatures upstream of the preburners. If the restart model shows the preburner temperature to be a driver for restarting the engine, higher temperatures could be achieved by having a longer cutoff purge to warm the preburner.

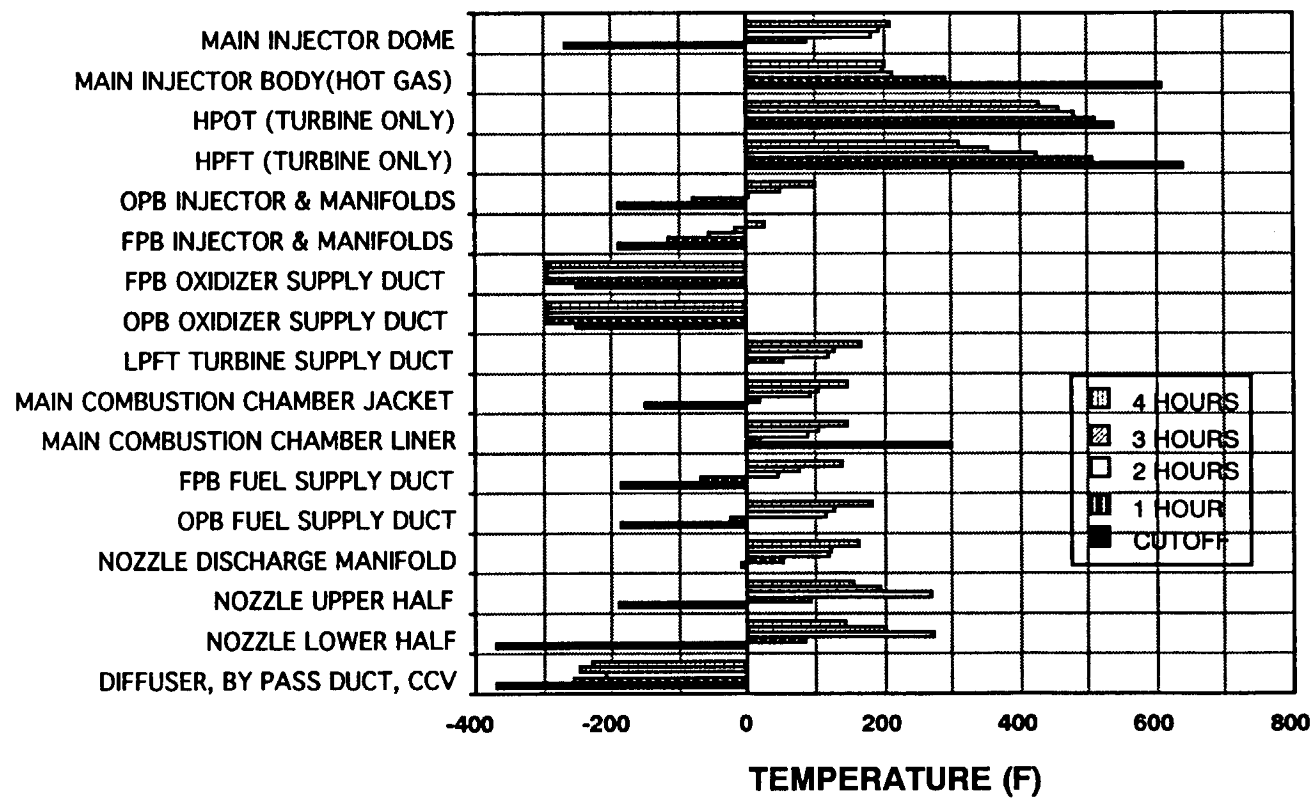

SSME TMM HEAT SOAKBACK CASE 16
LH2 re-circulation flow = 1. lbm/sec LOX re-circulation flow = 1. lbm/sec
Solar heating = 429 btu/ft2-hr half of the surface area
HPOT
OPB Injector & Manifold
T(35)
T(1002)
T(1002) Ground Start Condition
Temperature, degree F
600
510
420
330
240
150
60
-30
-120
-210
-300
0
5000
10000
15000
Time, seconds

SSME Upper Stage Use
Engine Component Temperature Trends

This chart summarizes the temperature trends for the engine components excluding the prechilled turbomachinery and interconnect ducting. Temperatures are plotted for cutoff, one, two, three, and four hours after cutoff.

SSME Upper Stage Use

ENGINE COMPONENT TEMPERATURE TRENDS
DURING COAST PHASE
(EXCLUDES TURBOPUMPS)



TA3–0221

SSME Upper Stage Use

Recirculation and Thermal Control Analysis

In order for the turbomachinery to function properly, preconditioning is conducted for ground starts in the form of recirculation for the LH2 and a bleed system for the LOX. Recirculation was utilized for both the fuel and oxidizer systems in the J 2 engine of the SIVB stage of the Apollo to maintain proper inlet conditions and hardware temperatures for the pumps.

The effects of thermal control systems were evaluated in this study to lower the tank pressures needed for pump NPSP.

Recirculation was examined for both the fuel and oxidizer system upstream of the main propellant valves. Temperatures for the low pressure pumps, high pressure pumps and ducting were predicted. Flowrates ranging from half a pound up to three pounds per second were assessed. Hardware temperatures were analyzed immediately following engine cutoff and at intervals later in the coast period prior to engine restart.

In addition to recirculation, insulation and thermal control paint were evaluated to determine their effectiveness for thermal control for the oxidizer turbomachinery and ducting. The fuel pumps and ducting already have insulation so only the thermal control paint was evaluated on the fuel system.

SSME Upper Stage Use

Recirculation and Thermal Control Analysis

- Effect of Recirculation
  - LOX Recirculation from Inlet Through Low Pressure LOX Pump, then Duct and Through High Pressure LOX Pump
  - H2 Recirculation from Inlet Through Low Pressure H2 Pump, then Duct and Through High Pressure H2 Pump to Main Fuel Valve
  - Flowrate From 0.5 – 3.0 lbm/sec
    - Same Flowrate Used For Both LOX and H2
  - Examined Right After Shutdown and Later in Coast

- Effect of Insulation
  - On LOX Low Pressure Pump and Discharge Duct
  - Already on H2 Turbomachinery

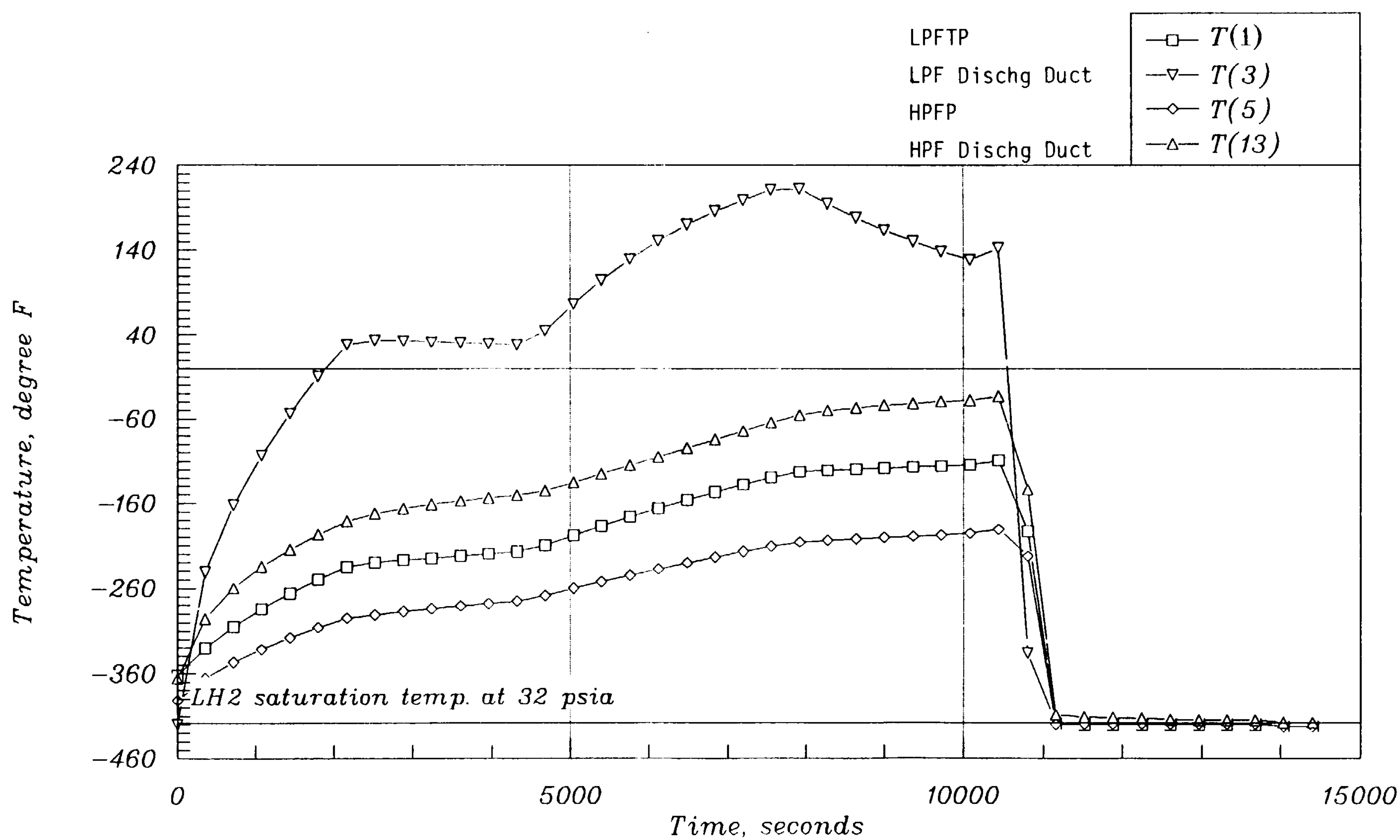
- Thermal Control Paint
  - On LOX Low Pressure Pump and Discharge Duct
  - On H2 Low Pressure Pump and Discharge Duct

SSME Upper Stage Use
Recirculation Analysis

This plot is of a case that was run to determine the impacts of delaying propellant recirculation for the engine during the coast period to conserve propellants in the event of the need for a longer coast period. This case also shows why recirculation should begin shortly after EOIBCO to condition the turbopumps for restart. The propellant recirculation for this case was not started until 3 hours after EOIBCO.

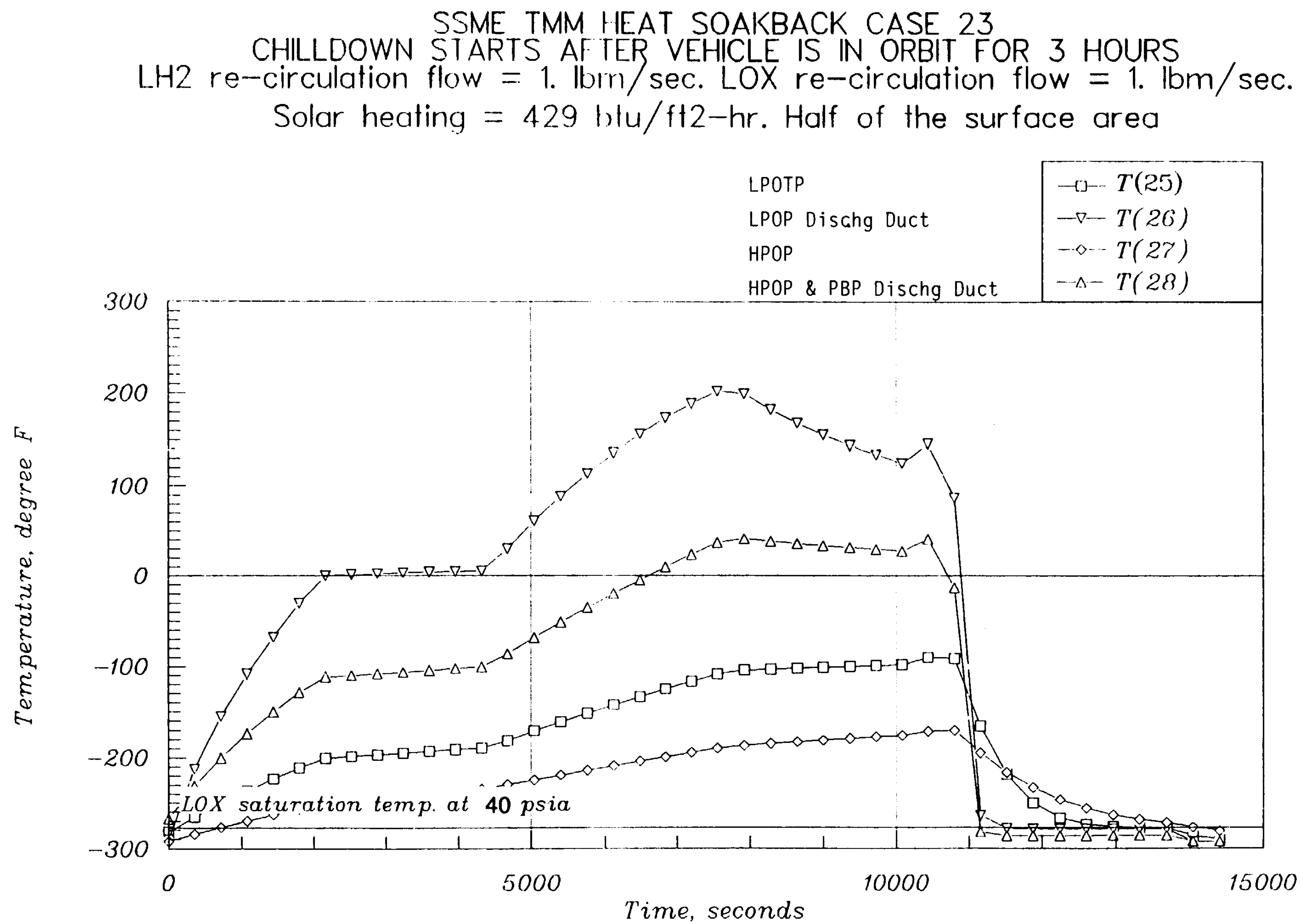
The fuel turbopumps and interconnecting duct are shown to require approximately one thousand seconds of prechill to re-establish conditions for restart after the recirculation begins.

SSME TMM HEAT SOAKBACK CASE 23
CHILLDOWN STARTS AFTER 3 HOURS IN ORBIT
LH2 re-circulation flow = 1. lbm/sec. LOX re-circulation flow = 1. lbm/sec.
Solar heating = 429 btu/ft2-hr. Half of the surface area



SSME Upper Stage Use
Recirculation Analysis

This plot shows the LOX turbopumps and interconnecting ducts for the same case as the previous plot. This case also includes the thermal control paint on the LOX ducting. The prechill time required to re-establish conditions for restart is longer than that required for the fuel turbopumps due to the thermal properties of LOX. Approximately twenty five hundred seconds (42 minutes) of prechill recirculation is required to re-establish conditions for restart.

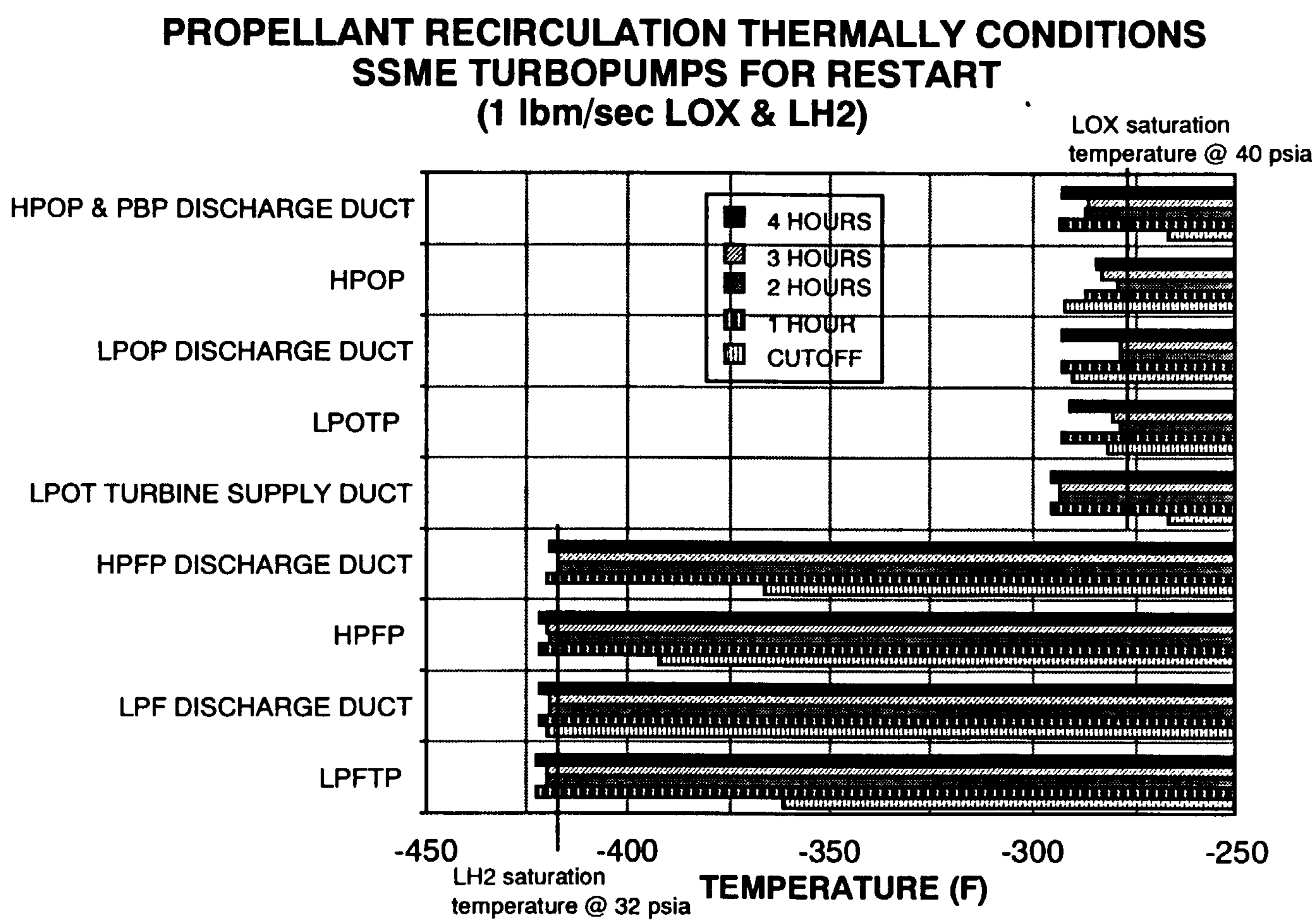

SSME TMM HEAT SOAKBACK CASE 23
CHILLDOWN STARTS AFTER VEHICLE IS IN ORBIT FOR 3 HOURS
LH2 re-circulation flow = 1. lbm/sec. LOX re-circulation flow = 1. lbm/sec.
Solar heating = 429 btu/ft2-hr. Half of the surface area
LPOTP
LPOP Dischg Duct
HPOP
HPOP & PBP Dischg Duct
T(25)
T(26)
T(27)
T(28)
300
200
100
0
-100
-200
-300
Temperature, degree F
LOX saturation temp. at 40 psia
0
5000
10000
15000
Time, seconds

SSME Upper Stage Use
Propellant Recirculation

This chart summarizes the temperature trends of the turbomachinery and interconnect ducting which has recirculation flow for thermal conditioning. Temperatures are plotted for cutoff, one, two, three, and four hours after cutoff.

TA3–0220A

SSME Upper Stage Use



TA3–0220

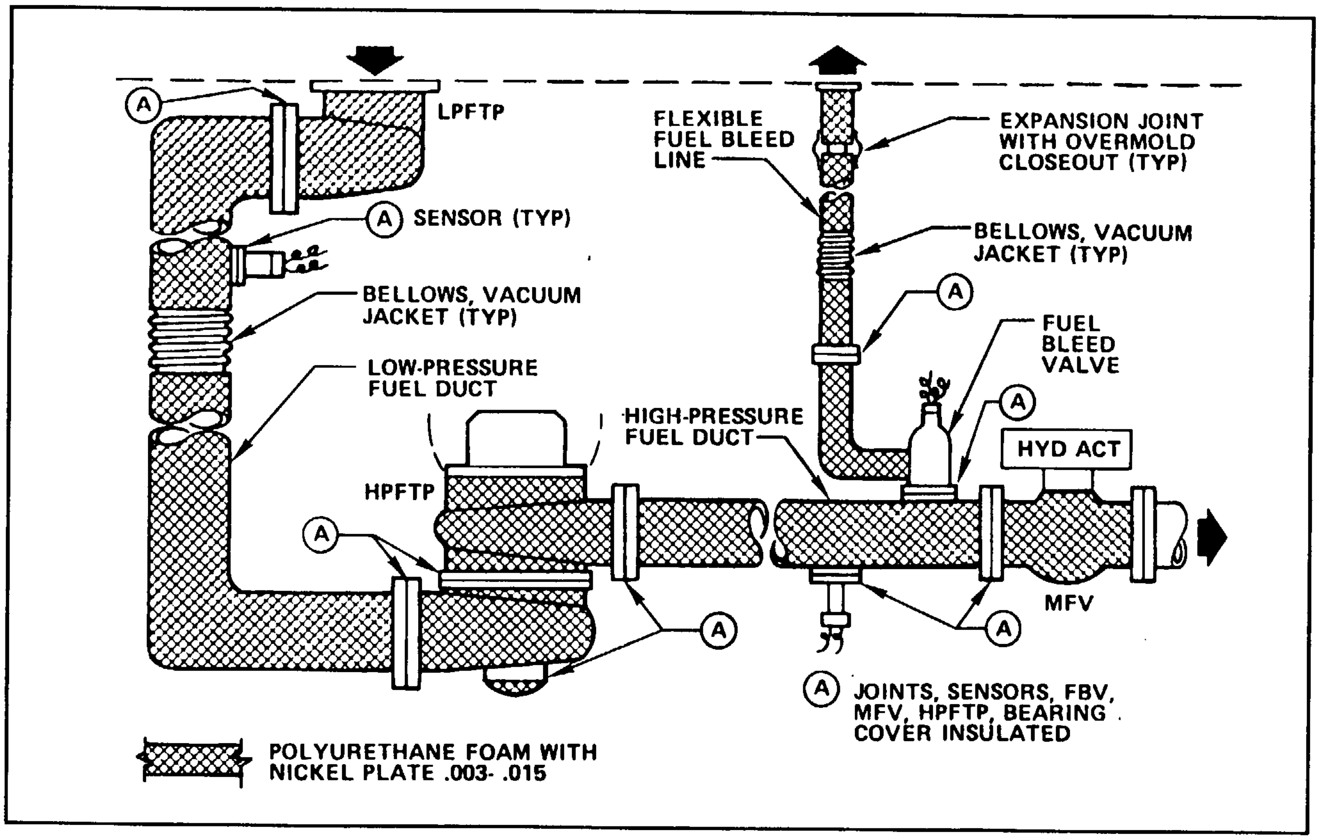
SSME Upper Stage Use
Current Insulation on SSME

Insulation is currently used on the SSME LH2 ducting and turbomachinery to prevent liquid air from forming and potentially dripping on to other sensitive components such as valve actuators and instrumentation related hardware.

The insulation is polyurethane foam with a nickel plate shell to form an air tight seal and provide a protective durable coating. The surface of the insulation is not ideally designed to prevent absorption of thermal energy.

SSME Upper Stage Use
Current Insulation on SSME

- **Purpose**
  - **Prevent Liquid Air from Forming and Dripping on Other Sensitive Components**



C-2

TA3-0291

SSME Upper Stage Use
Pump Inlet Thermal Control Results

The facing page table summarizes the effects of insulation and thermal control paint on the temperatures just upstream of the LOX and H2 turbomachinery (and thus on the tank pressures needed for restart). Recirculation flow is assumed at one lbm/sec. If no insulation is used on the LOX side (insulation is already present on the H2 side on the nominal SSME) and no thermal control paint is used, then the baseline conditions of 181.4 °R on the LOX side and 40.3 °R on the H2 side are achieved at the worst time of the solar portion of the orbit. These temperatures are too high if a low stage pressure is desired.

The second case shows the effect of adding insulation on the LOX side but it produced little improvement. The model used does not take advantage of the insulation's nickel coating as a reflector. Although not all of the energy input is in the wavelength band where nickel is reflective (or, for that matter, where the paint is reflective), most of the energy is in such a band. Consequently, the third case shows the best that could be achieved if the nickel coating is very clean and smooth. Reality would lie somewhere in the band between cases two and three. Case four analyzed the effect of a thermal control paint, without insulation on the LOX side, and not using any additional reflectivity from the nickel (it would be painted over). The paint is very effective at reflecting energy from sunlight and reflected sunlight (Earth albedo). It was assumed totally ineffective against the Earth's blackbody radiation. This case of using paint produced temperatures which allow low tank pressures throughout the orbit.

The recirculation flow could be used to do the same job as the paint by carrying away the heat (the paint prevents the heat from arriving). The last case shows the flowrate needed to achieve the same effect as the paint.

SSME Upper Stage Use
Pump Inlet Thermal Control Results

Rotating Stage in Sunlight

Case	Recirculation Flowrate, lbm/sec		Wall Temperature, °R Pump Inlet	
	LOX	H2	LOX	H2
No Insulation or Paint	1.0	1.0	181.4	40.3
LOX Insulation	1.0	1.0	179.8	40.3
LOX Insulation with Nickel Coating Effective as Reflector*	1.0	1.0	172.7	39.0
Thermal Control Paint, No Insulation**	1.0	1.0	169.5	38.6
No Insulation or Paint	4.04	4.04	169.5	38.6
Recirculation Fluid Temperatures: LOX at 163.7 °R and H2 at 36.7 °R				

* Best case of absorptance equals 0.40. This and the previous case bound the potential effects of insulation.
** Absorptance equals 0.18.

TA3–0292

SSME Upper Stage Use

Recirculation Analysis

Recirculation of the propellants was investigated parametrically to determine the minimum flowrates that could be used to achieve satisfactory turbomachinery temperatures for restart. As was shown earlier in the graphs a flowrate of one pound per second achieved temperatures acceptable for restart with adequate NPSH margin. To provide the earliest restart time, recirculation should be start shortly after the EOIBCO.

Recirculation for the LOX system was shown to work with one pound per second but the NPSH margin was insufficient when the stage was on the solar side of the earth. In subsequent modeling both insulation and thermal control paint were evaluated for reducing the temperature rise of the LOX turbomachinery components. The thermal control paint was shown to be more effective in reducing the temperature rise thus providing more consistent and adequate NPSH margin during the solar portion of the orbit. The thermal control paint reduces the absorptivity and increases the emissivity of the component surface.

The recirculation flowrates appear to be less than required for stage repressurization, however this requires further investigation since actual restart times have not been established.

SSME Upper Stage Use

Recirculation and Thermal Control Analysis Conclusions

- Recirculation Flows Parametrically Investigated
  - Liquid Hydrogen Flow Of 1.0 Lbm/Second Is Recommended
    - Start Immediately After Cutoff To Provide Earliest Restart Capability
  - Liquid Oxygen Flow Of 1.0 Lbm /Second Is Recommended
    - Starting Within 5 Minutes Of Cutoff To Provide Earliest Restart Capability
  - Both Insulation And Thermal Control Paint Examined To Reduce Temperature Rise In LOX Turbomachinery And Ducting During Solar Portion Of Orbit
    - Adequate NPSH Margin Continually Maintained
  - Thermal Control Paint Produced More Consistent And Higher NPSH Margin
- Recirculation Flowrates Appear Less Than Needed For Stage Repressurization

TA3-0180

SSME Upper Stage Use
Moisture Assessment

Based on the results of the thermal analysis, engine cutoff data, and recent hot fire post-test inspections conducted on the NASA MSFC Technology Testbed engine, the behavior of moisture in the engine can be predicted with greater confidence. The results to date suggest that the potential for moisture influence on the engine restart appears to be very low. The areas of concern in the engine are the components where combustion takes place (preburners and main injector) and the high pressure turbopump turbines.

The thermal analysis showed that the turbine bulk hardware temperatures remain above 300 degrees F up to four hours after engine cutoff. This will ensure that water in the hot gas section of the engine will be vaporized and therefore be removed from the engine with the cutoff purges. In addition, the thermal analysis showed that after cutoff the temperatures of the preburner injector and manifolds warm up slowly from temperatures below -150 degrees F, however, the standard cutoff purges should prevent any potential for orifice blockage from ice formation.

Also evaluated was the main injector. The thermal analysis revealed that temperatures would reach ambient in one hour, which will allow any remaining water in the injector to be vaporized.

Additional post-test inspections conducted with special procedures for isolating the engine and its combustion produced moisture from the environment should be conducted to further quantify the moisture which exists in the engine at altitude cutoff.

SSME Upper Stage Use
Moisture Assessment

- Potential For Moisture To Influence Engine Restart Appears To Be Low
- Engine Temperature Should Remove Moisture
  - High Pressure Turbines Remain Above 300 Degrees F
  - Preburner Injector And Manifolds Warm-up Slowly
    - Injector Orifice Blocking Should Not Occur
  - Main Injector Temperatures Reach Ambient Within 1 Hour
- Should Be Demonstrated In Test

SSME Upper Stage Use
Moisture Assessment Plan

The moisture assessment program shown has four major phases and can have large portions conducted with the MSFC NASA Technology Testbed SSME. Characterization and simulated altitude start can be conducted completely at the TTB. Development of the orbital restart criteria can be developed with some added risk at the TTB, however the Arnold Engineering Development Center (AEDC) could provide a vacuum environment to provide a more representative simulation. The final demonstration of the orbital restart should be conducted at the AEDC.

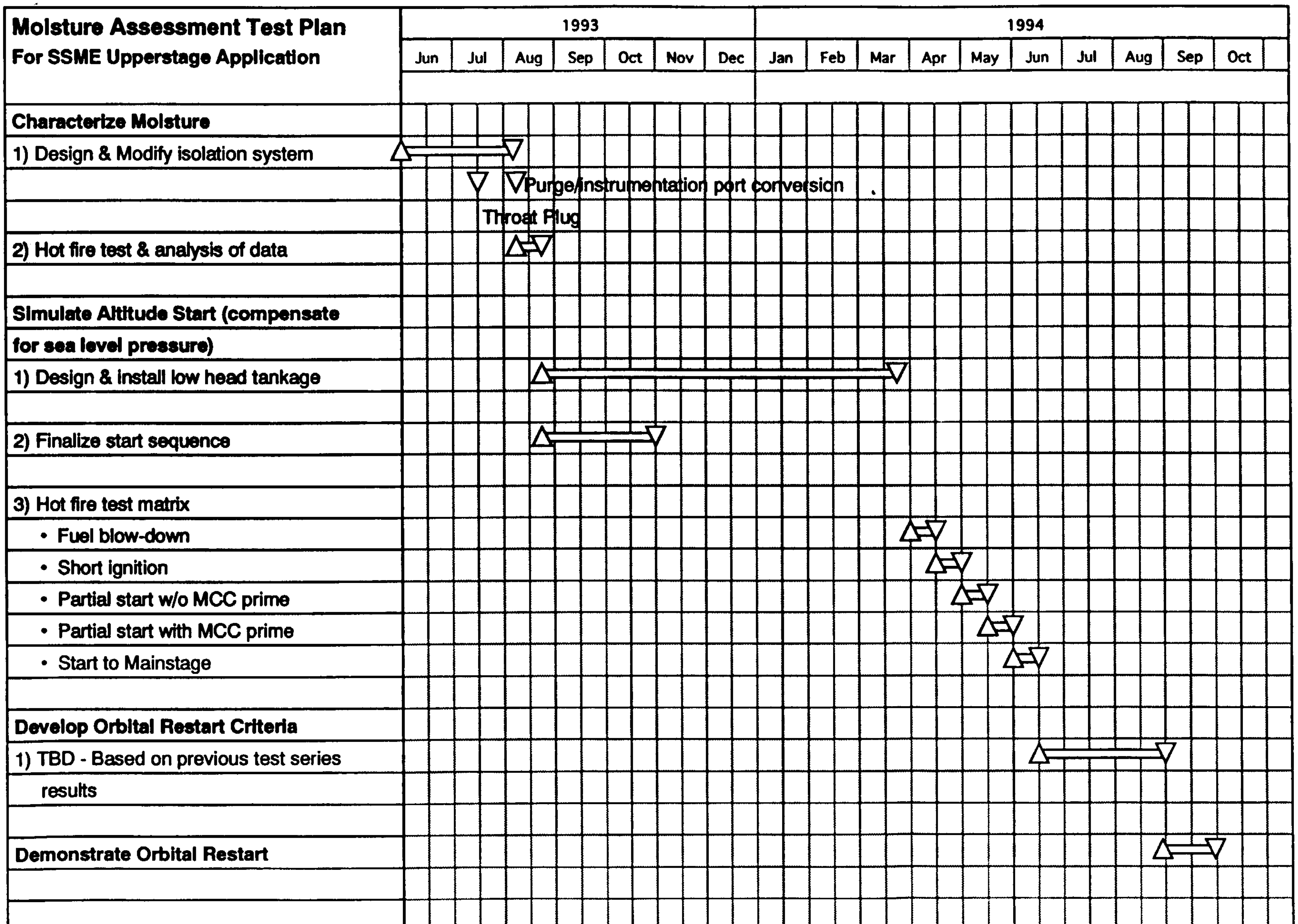
Moisture characterization would be determined by operating the engine in a nominal engine hot fire test and shutdown followed by an addition of an isolation trickle purge via an existing instrumentation port in the Main Injector LOX dome to prevent atmospheric moisture from entering the engine until a modified throat plug could be installed into the Main Combustion Chamber. The modification to the engine is minimal involving adaptation of an existing instrumentation port to accept a facility helium purge line. A ground support throat plug also requires only minimal modification by attaching a dew point measurement device and a vacuum line port to accept a vacuum source. With the plug installed a dew point would be measured immediately and then a vacuum would be pulled on the engine system to simulate the environment of space when the engine shuts down after the proposed altitude burn. Upon completing the initial measurements a series of vacuum /dew point measurement cycles would be conducted periodically until the engine reached ambient temperatures as predicted by modeling of the preburner and preburner injectors. The nominal engine drying purge would not be conducted during this moisture characterization analysis as this would bias the results by potentially removing any moisture that may be present in the engine. By conducting this analysis the presence of moisture in the engine associated with combustion can be assessed. If moisture is detected then the effectiveness of the coast period before restart to remove that moisture can be evaluated. If it is found that significant moisture is in the engine and it proves difficult to remove measures for mitigation ,such as warmant purges, can be investigated.

Simulated altitude starts could be conducted after the moisture assessment is completed. Significant modification of the facility is required in order to provide the low inlet pressure conditions that will exist for the upperstage; currently the tankage provides STS level head conditions. The altitude start sequence would be finalized based on the results of the moisture assessment and evaluation of the actual engine inlet conditions produced by the facility modifications. The start sequence would be progressively developed by incrementally adding elements to the start sequence such as component primes and operational phase changes. Initially, the start sequence would be based on the model/study findings and then modified if necessary based on the actual behavior of the engine in the incremental start sequence to achieve the desired start sequence characteristics.

Once the start sequence is established the restart criteria could be established and demonstrated. The engine currently is thoroughly inspected and performance/sensor data is analyzed after every firing. For the restart no inspections can be performed and not all the data can be evaluated in the time available prior to restart. Therefore, a criteria must be established that will provide high confidence in an efficient manner that the engine is acceptable for restart. The experience base of the SSME will play a key role in the determination of this criteria along with current data processing capabilities of analog and digital information. The verification of the restart criteria would be conducted demonstrating restart of the engine on the TTB or other teststand without engine inspections and utilizing the restart criteria assessment. The study was not structured to define a restart criteria.

The demonstration of orbital restart for the SSME should be conducted at AEDC J-4 vacuum test cell to provide the closest possible simulation to the actual conditions which the engine will experience in orbit. The vacuum environment plays a key role in the condition of the engine at shutdown and during the coast period prior to the restart and how the engine will respond during the restart sequence.

SSME Upper Stage Use
Moisture Assessment Plan



TA3–0429

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Orbital Restart Analysis

TA3-0278

SSME Upper Stage Use
Orbital Restart Analysis Approach

The basic start sequence for the orbital restart was established by the altitude start analysis. The valve schedule and positions were derived from the altitude case to accommodate the lower tank pressures which are identical for the orbital restart case.

The major difference between the orbital restart and the altitude start is the thermal environment and the consequent engine component hardware temperatures. Depending on the amount of time after the first burn cutoff, the hardware temperature can vary significantly as was demonstrated on the SIVB stage of the Apollo vehicle.

To define the temperatures expected on the SSME hardware, a thermal model was used to predict temperatures versus coast time. The SSME transient start model was used with temperatures defined from the thermal model and with temperatures of key components varied from ground temperatures one at a time to define start sensitivities. By utilizing this technique, the minimum amount of heating and cooling required to start the engine with little risk was defined. The majority of the cases run with the transient model were for coast times of 7,500 seconds and 10,000 seconds. These times corresponded to temperature variation extremes as a result of position on the solar side or shadow side of the earth. At this time range, most of the components had reached near-ground start thermal conditions. This time range also corresponded with the Apollo restart experience base which had an average restart of approximately 8,400 seconds. Restarts of the engine at earlier times were examined also, but were found to require additional heating of components.

SSME Upper Stage Use

Orbital Restart Analysis Approach

- Use Start Sequence Derived for Altitude Start Case
  - Valve Positions and Ramp Rates

- Use Inlet Pressures From Altitude Start Case
  - LOX – 40 psi
  - H2 – 32 psi

- Use Thermal Analysis Results for Hardware Versus Coast Time
  - Vary One Component Temperature at a Time to Ground Thermal Conditions to Establish Start Sensitivity
  - Determine Minimum Component Heating/Cooling Required

- Analyze Start at 7,500 and 10,100 seconds of Coast
  - Sun and Shadow Starts
  - Maximum and Minimum Nozzle Temperatures
  - Most Components Close to Ground Start Thermal Conditions
  - Earlier Than Apollo Starts
  - Examine Earlier and Later Starts

SSME Upper Stage Use

Hardware Temperatures for Transient Model Simulation

Key hardware temperatures in the engine components were evaluated by the transient model at times of 7,500 and 10,000 seconds after cutoff. Upon running these cases initially without component heating, it was determined that the engine could restart but would operate under a regime with higher risk and well outside of the SSME experience base. Component heating was systematically added to the engine components with lagging temperatures until a start sequence close to the SSME experience base was achieved. Recirculation and thermal control paint were assumed to be utilized for the final cases.

SSME Upper Stage Use

Hardware Temperatures for Transient Model Simulation

Element Description	Aerothrm Node	Ground Start, °R	7,500 sec Restart, °R		10,100 sec Restart, °R	
			Unheated	Heated	Unheated	Heated
LPFP Inlet	T1	37	39	–	37	–
LPFP Discharge	T3	37	42	–	37.5	–
HPFP Discharge	T5	37	41	–	37.5	–
CCV	T21	530	260	485	195	485
MFV Discharge	T21	530	260	530	195	530
Nozzle Inlet and 1st Half	T19	530	730	–	510	–
Nozzle 2nd Half & Outlet	T18, T20	530	730	–	520	–
MCC Inlet	T16, T17	530	560	–	550	–
MCC 1st Half	T16, T17	530	560	–	550	–
MCC 2nd Half	T16, T17	530	560	–	550	–
PB Fuel Supply *	T23	530	590	630	540	605
OPB Injector	T1002	540	475	–	500	–
OPBV	T40	540	167	-	165	–
OPB Ox Supply Line	T40	500	167	500	165	500
FPB Injector	T1001	540	410	–	440	–
FPOV	T44	540	315	–	277	–
FPB Ox Supply Line	T43	400	167	–	165	–

- Recirculation and Thermal Control Paint Assumed

* This Component is not Heated. The Temperature Increase Under the "Heated' column is Due to Heating the MFV Discharge.

TA3–0281

SSME Upper Stage Use
Key Components Impact Orbital Restart

The thermal analysis of the engine components revealed that significant variations and responses occur once the engine shuts down from its first burn. Components with large surface areas and low relative masses, such as the nozzle, responded with dynamic behavior, while components buried down in the middle of the engine such as the fuel preburner injector and oxidizer preburner oxidizer supply line, tended to be less dynamic. Most components trended toward ambient temperature. However, two component areas critical for controlling mixture ratio in the initial phase of the start sequence were found to lag behind the remainder of the engine components.

For example, the nozzle, as shown on the facing page, represents components which experience large variations in temperature as the vehicle goes from the solar side to the shadow side of the earth. Consequently, cases were picked to specifically examine the impact of these variations on the restart (the two dashed lines at 7,500 seconds and at 10,100 seconds). Both extremes had sufficient energy for the start and neither extreme hampered the start sequence.

There is also a class of components, exemplified by the FPB injector on the facing page chart, which start too cold to allow a start but which steadily rise in temperature. Components of this type would require heating early, but at some temperature (i.e., at some time after the orbital insertion burn) would be warm enough to allow restart without that particular component needing additional heating. 7,500 seconds was found to be the time necessary for components of this type (see the example of the FPB injector on the facing page and note that the temperature does not necessarily have to rise all the way to the ground start conditions for all components).

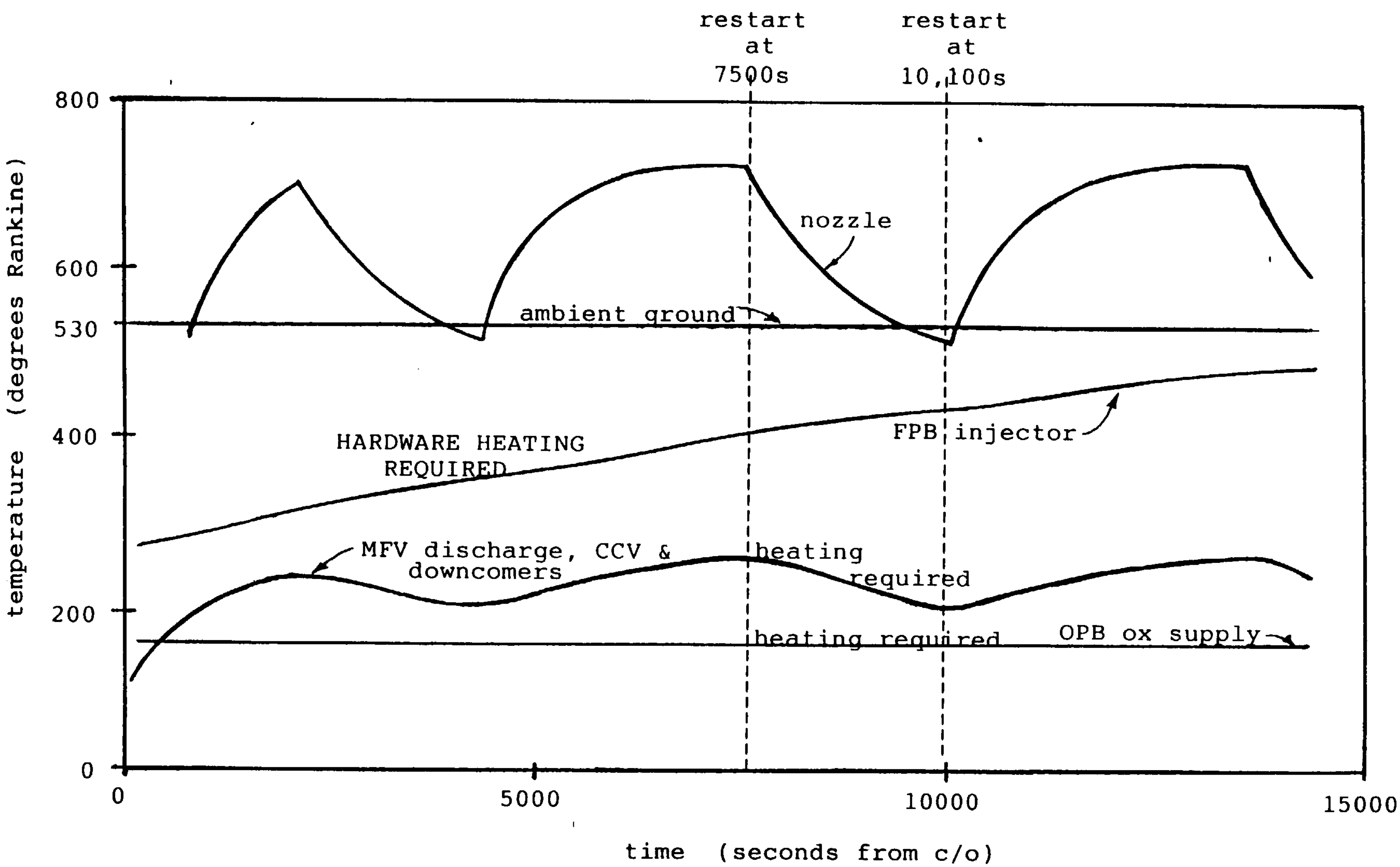
The third class of components, also shown on the chart as the lowest two curves, are those that start cold and stay cold. If these components are nominally at ambient ground conditions for the SSME ground start, then they will need heating, though not necessarily to full ground ambient, to keep the restart within the SSME experience base. This is particularly true of those components which affect the mixture ratio during the earliest part of the start sequence.

Transient start modeling of the SSME was conducted with the thermal model inputs at coast period times of 7,500 and 10,000 seconds. The analytical modeling results for the orbital restart indicated that component heating would be necessary for the oxidizer preburner oxidizer supply duct and the Main Fuel Valve and immediately adjacent ducting. Note that the MFV currently has a heater on the existing SSME to avoid freeze up of the hydraulic actuator.

TA3–0286A

SSME Upper Stage Use

Key Components Impact Orbital Restart



TA3–0286

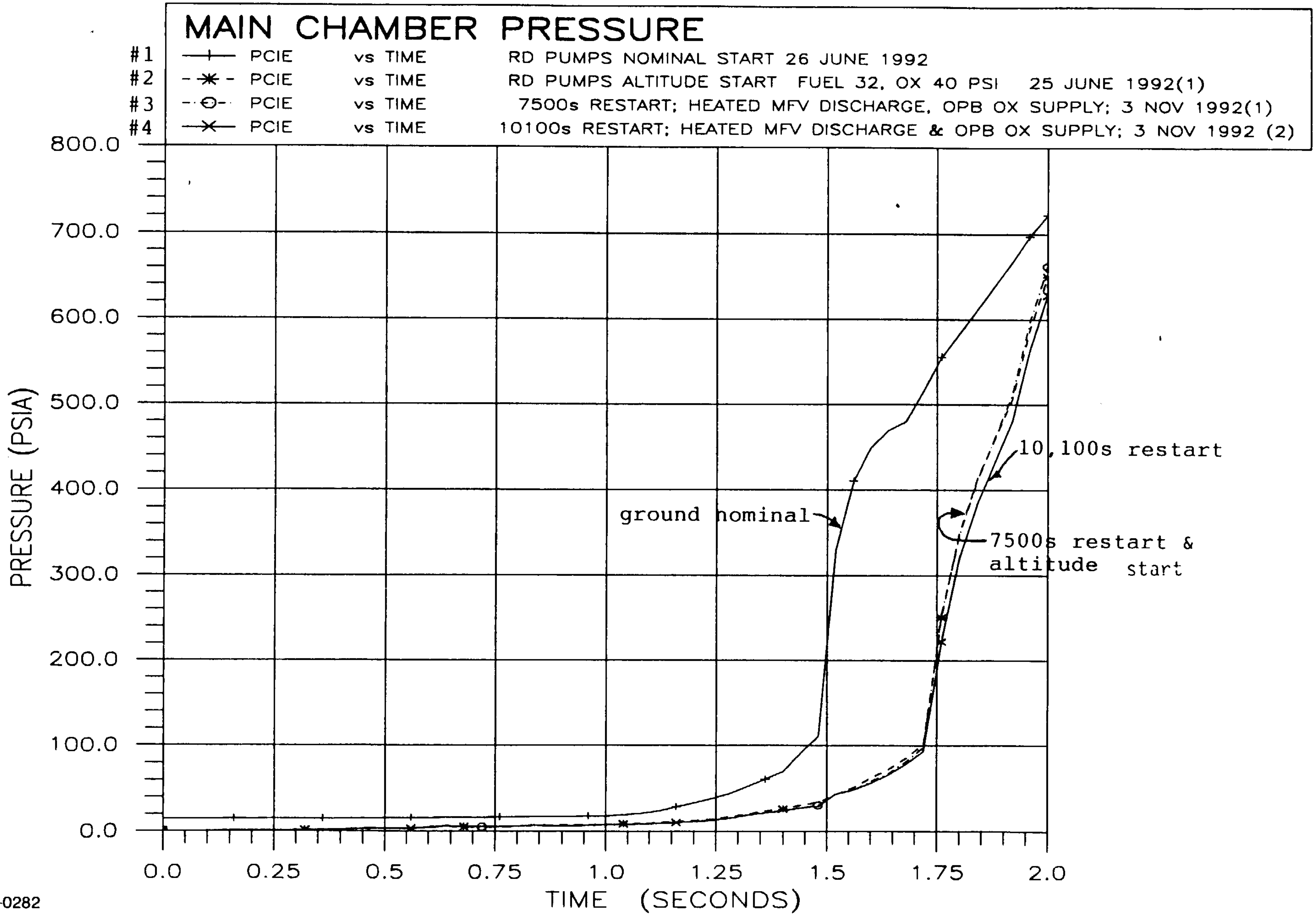
SSME Upper Stage Use

Orbital Restart Combustion Chamber Pressure

Comparing the main chamber pressure profiles with time shows effectively the variation between the start response of the nominal ground start and the restart cases evaluated with the transient model. The 7,500 second coast period case falls almost directly on top of the altitude case that was previously analyzed. The 10,000 second case lags slightly in the thrust buildup from the altitude case, but is not significantly different. The previous altitude start case converged with the nominal ground start case at ~ 2.4 seconds. The orbital restart cases converge as well at ~ 2.4 seconds which is expected since the critical component temperatures have either reached or are relatively close to the ground nominal case engine temperatures.

SSME Upper Stage Use

Orbital Restart Combustion Chamber Pressure



TA3–0282

SSME Upper Stage Use
Restart Conditions

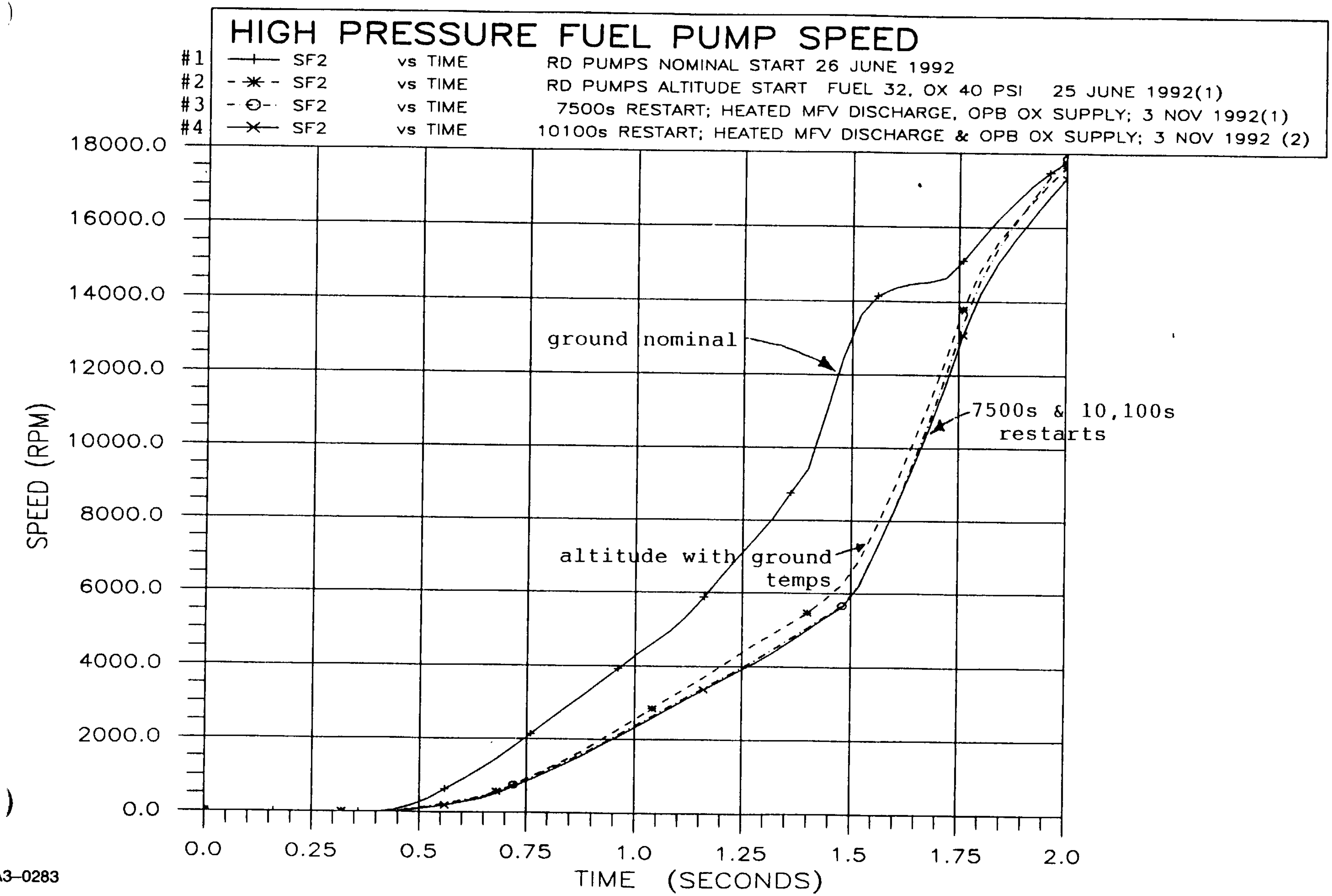
The following three charts show the key component parameter behavior for the ground nominal start, and orbital restarts at 7,500 and 10,000 seconds. These parameters correspond with the cases shown on the previous chart with main chamber pressure versus time.

For the two orbital restart cases, the fuel turbopump speed does not vary drastically from the altitude case. The restart cases have slightly slower ramp-ups for the turbine speed, but was found to be acceptable.

The turbine temperatures for the fuel and LOX high pressure turbopumps were evaluated as well and found to be acceptable with temperature spikes occurring within desirable ranges.

SSME Upper Stage Use

High Pressure Fuel Pump Speed



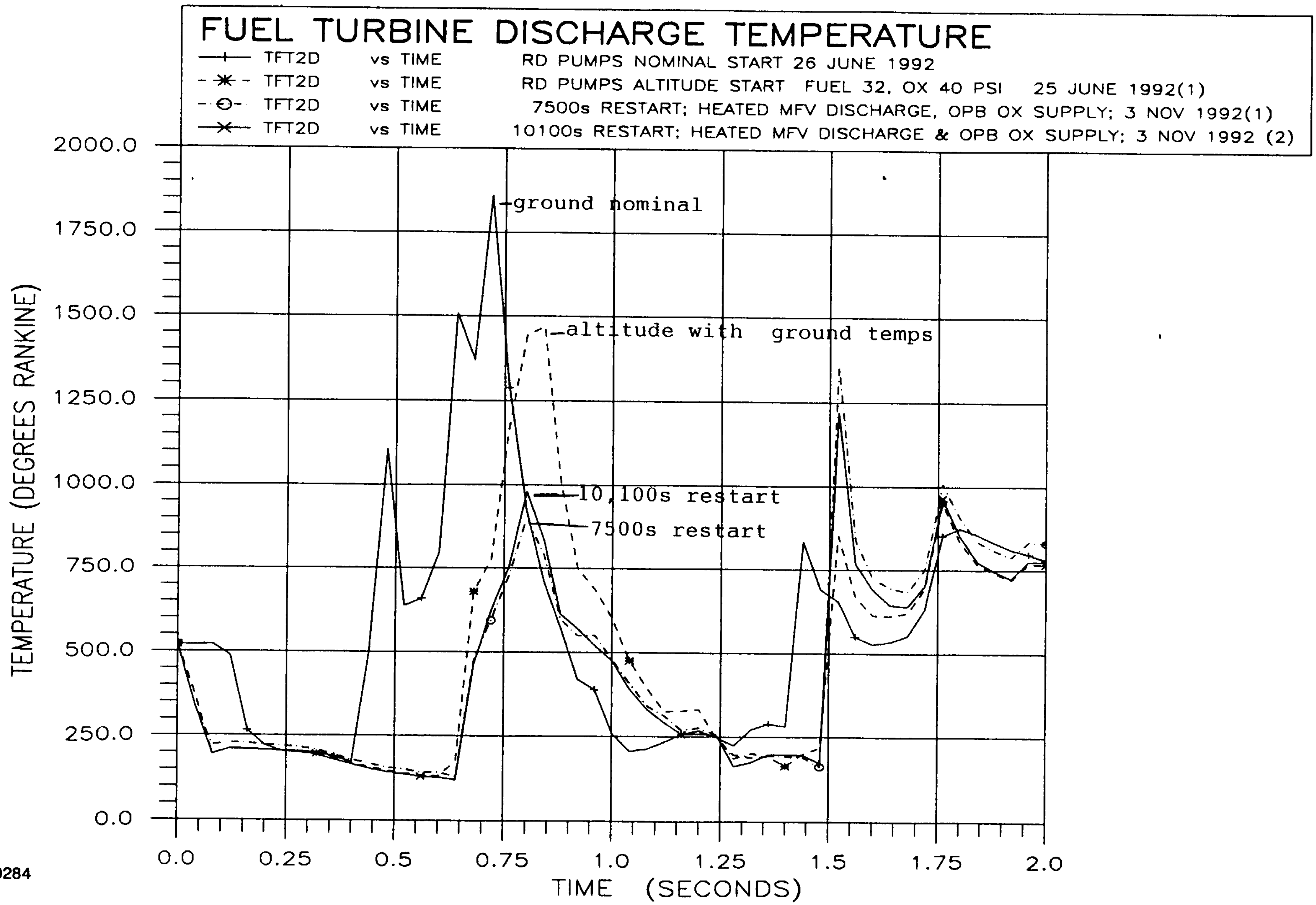
TA3–0283

SSME Upper Stage Use
Orbital Restart Results

Refer to the previous annotation.

SSME Upper Stage Use

Fuel Turbine Discharge Temperature



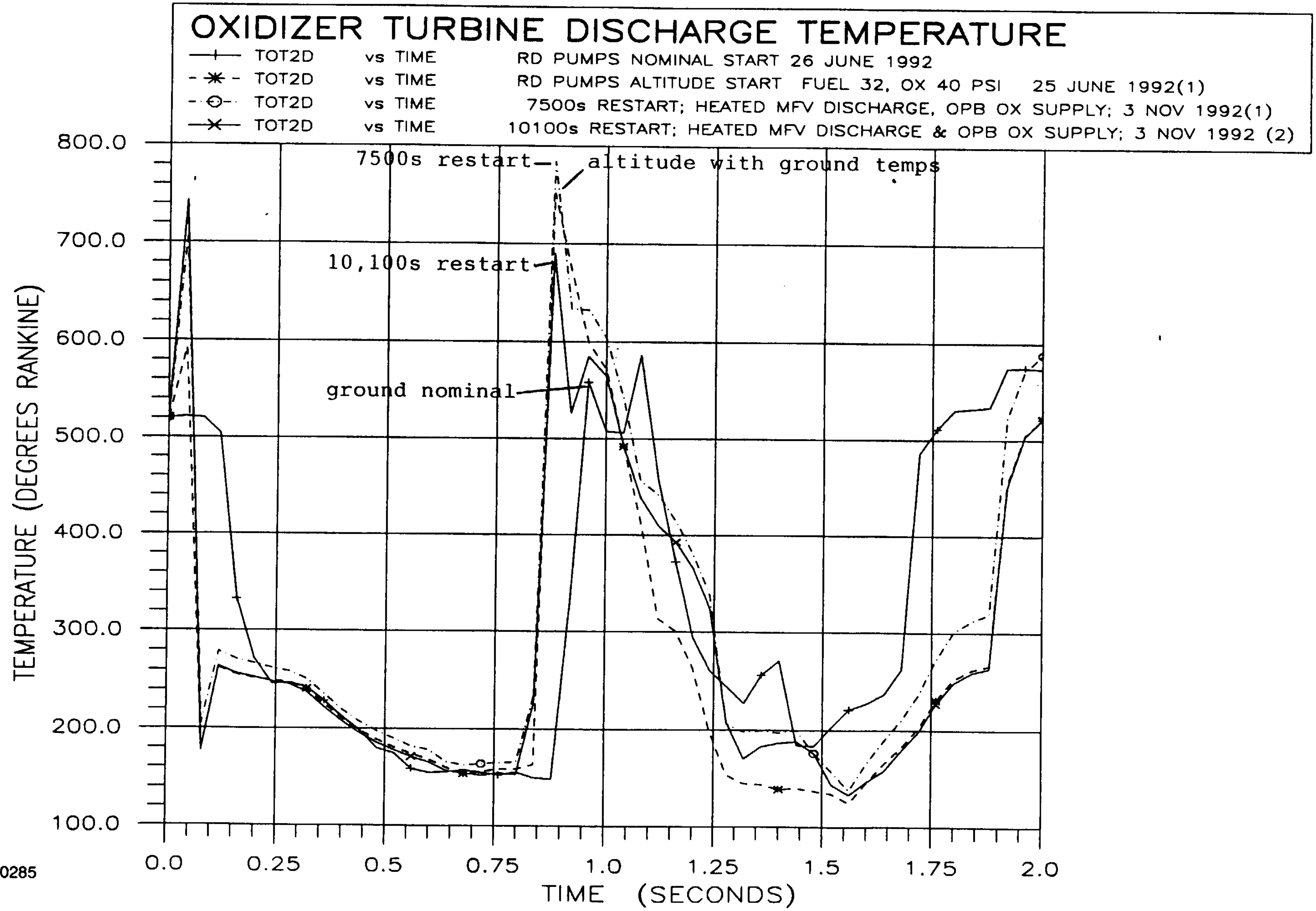
TA3–0284

SSME Upper Stage Use
Orbital Restart Results

Refer to the previous annotation.

SSME Upper Stage Use

Oxidizer Turbine Discharge Temperature

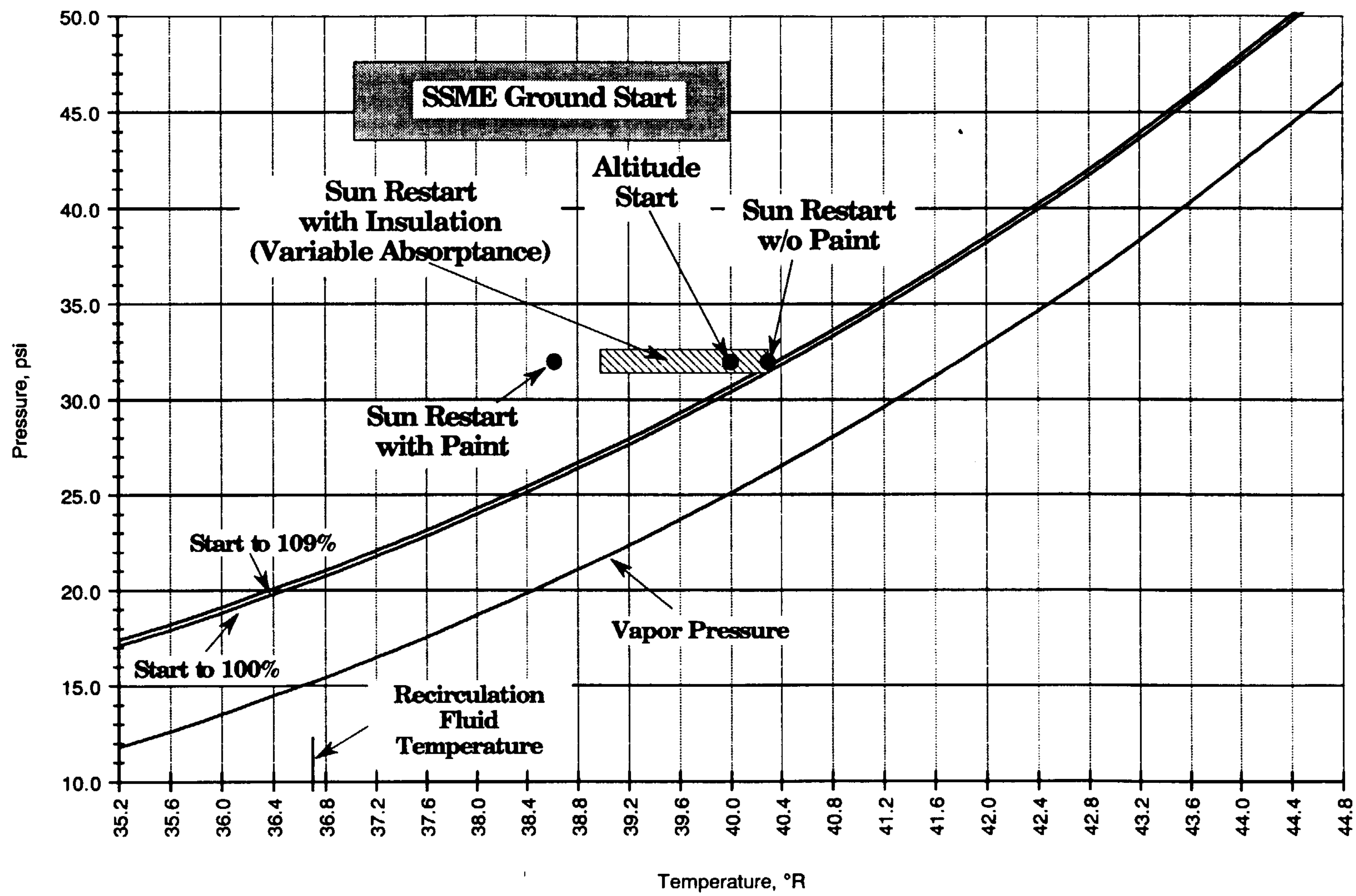


TA3-0285

SSME Upper Stage Use
Fuel Conditions for Start

The inlet conditions for the liquid hydrogen must satisfy specific pressure and temperature requirements in order to provide sufficient net positive suction pressure (NPSP) for the low pressure fuel pump and the high pressure fuel pump. The facing page chart summarizes the start conditions for all the cases examined in the study. Minimum NPSP curves are plotted for both 109% and 100% power levels along with the vapor pressure curve for liquid hydrogen. The operating point for the engine must be above the NPSP curves to prevent detrimental cavitation from occurring in the pumps. The shaded box marked "SSME Ground Start" shows the specification start conditions for the current SSME start at liftoff. The altitude start case that was evaluated for a tank pressure of 32 psia is shown. The altitude case represents the lowest pressures that could be used with an SSME assuming that the hydrogen is delivered at the highest temperature of the current ground start conditions. The restart cases are shown, all for the worst time during the orbit which is on the sun side. The case without paint and without assuming any heat reflection from the nickel coating of the insulation is marginal. The restart case using thermal control paint produces significant margin.

Fuel Conditions for Start



TA3–0306

SSME Upper Stage Use
Oxidizer Conditions for Start

The oxidizer system requirements for pump inlet conditions are similar in character to those of the fuel system. There is also a remote possibility that helium ingestion can take place in the oxidizer system, so that NPSP requirements for that condition are also included on the facing page chart. The ground start is above 100 psi due to the head contribution provided by the LOX tank location in the top portion of the Shuttle external tank. Not all of the pressure is needed to satisfactorily operate the low pressure oxidized pump. The altitude case evaluated was basically the ground start case without the gravity head. The altitude case is shown and falls below the 109% power level NPSP line but above that needed for a start to 100%; however, starting above 100% power level was not required for the upper stage applications that was defined. If the need arose, a two step start could be implemented to allow acceleration head to be established prior to throttling above 100%. The restart cases for a restart on the sun side of the orbit are also shown. The basic case, without insulation or paint, is inadequate unless the pressure is raised significantly to about 47 psia. (Restart in the shadow side is possible at 40 psia.) However, use of thermal control paint produces significant margin for restart at 40 psia thus allowing reasonable sun side restarts.

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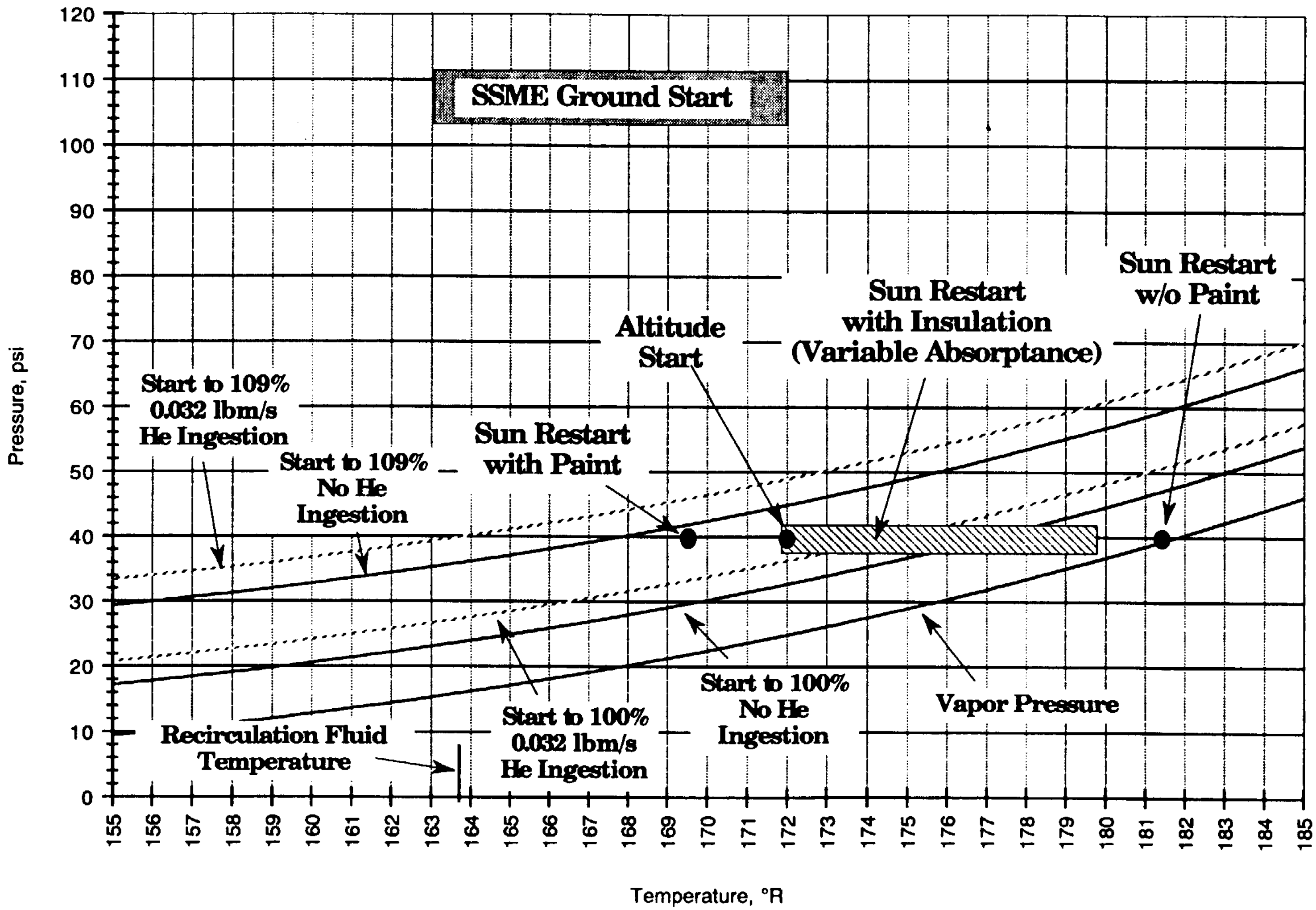
Oxidizer Conditions for Start



TA3–0306

SSME Upper Stage Use
Orbital Restart Conclusions

Just as was the case with an altitude start, an orbital restart of the SSME is feasible. Indeed a single start sequence (sets of valve controls) can be used for both cases. However, the orbital restart does have more additional constraints. Because the engine has fired and because of external heating, the engine must wait a length of time for acceptable thermal conditions and use some thermal conditioning. If ~120 minutes of wait is acceptable to the mission (Apollo was longer), then only a recirculation flow to the turbomachinery to lower NPSP requirements, and the heating of two small components to ensure proper mixture ratio to the preburners during the early part of the start transient, are required actions. One passive measure is also needed if tank pressures are to be kept low. Thermal control paint will lower the heat input to the turbomachinery during the solar portion of the orbit and thus lower the NPSP needed for a given recirculation flow.

No additional measures are needed for a start anytime after ~120 minutes.

SSME Upper Stage Use
Orbital Restart Conclusions

- Orbital Restart is Feasible
  - Start Sequence Same as Altitude Start
  - All Conditions Can be Made Satisfactory for Start After 7,500 Seconds
    - Restart Remains Feasible Thereafter
    - Apollo S-IV-B Stage Restarts Occurred After 8,500 Seconds
  - Earlier Restart Viable With Added Component Heating
  - Minimal Impact on Engine System
    - 7,500 Seconds Needed for Major Components to Reach Satisfactory Thermal Conditions
    - Propellant Recirculation
      - 1 lbm/sec LOX and 1 lbm/sec H2
      - For 90 Minutes Before Restart
    - Thermal Control Paint on LOX Turbomachinery and Ducting
      - Maintain Needed NPSH During Solar Portion of Orbit
    - Direct Heating of Two Components to Ground Ambient
      - Main Fuel Valve Discharge/Coolant Control Valve
      - Oxidizer Preburner Oxidizer Supply Duct
        - Mixture Ratio Control

TA3–0288

SSME Upper Stage Use
Requirements for Restart After 1 Hour Coast Period

The facing page chart shows the changes needed if an earlier restart, at one hour after cut-off, is needed by the mission profile. It basically means some additional components must be heated (for mixture ratio control) and that the recirculation flow start quickly. Further detailed modeling of the heating requirements to determine the minimum degree of heating is suggested if the one hour option is chosen.

SSME Upper Stage Use

Requirements for Restart After 1 Hour Coast Period

- Propellant Recirculation After 1st Burn Cutoff
  - 1 lbm/sec LOX and 1 lbm/sec LH_2
  - Small Delay May be Required for Contamination Abatement Assurance
- Thermal Control Paint on LOX Turbomachinery and Ducting
  - Maintain Needed NPSH During Solar Portion of Orbit
- Direct Heating of Components
  - Heating Required for Restart $\geq$ 7500 seconds
    - Main Fuel Valve Discharge/Coolant Control Valve - $\Delta T = \sim 290\ ^\circ R$
    - Oxidizer Preburner Oxidizer Supply Duct - $\Delta T = \sim 330\ ^\circ R$
  - Additional Heating Required for Restart at 1 Hour
    - Oxidizer Preburner Injector - $\Delta T = \sim 95\ ^\circ R$
    - Fuel Preburner Injector - $\Delta T = \sim 135\ ^\circ R$
    - Fuel Preburner Fuel Supply Duct - $\Delta T = \sim 140\ ^\circ R$
    - Oxidizer Preburner Fuel Supply Duct - $\Delta T = \sim 100\ ^\circ R$
- Verification of Additional Component Heating for Restart at 1 hour Suggested
  - Restart Modeling

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Conclusions

TA3-0274

SSME Upper Stage Use
Conclusions

The use of the SSME in an upper stage is feasible with minimal changes to the engine systems.

The altitude start case is especially easy, requiring only a change in the valve sequencing during start and reorificing of the ASI lines. Inlet pressures can be moderately low at 40 psia for the LOX and 32 psia for the H2.

The orbital restart case adds the need to recirculate propellant and thermal control paint (to keep the turbomachinery inlets cold to minimize the tank pressures needed), and the need to heat two small components (to maintain acceptable mixture ratios during the early part of the start). These actions allow start anytime after ~120 minutes. Earlier starts (~one hour) are also possible but would require additional component heating for mixture ratio control during the early portion of the start sequence.

SSME Upper Stage Use
Conclusions

- **Altitude Start Shown to be Feasible with Minimal Changes to Start Sequence**
  - Valve Resequencing
  - ASI Orifice Changes
  - Inlet Pressures
    - LOX ≥ 40 psi
    - H_2 ≥ 32 psi

- **Orbital Restart Shown to be Feasible**
  - Same Start Sequence as Altitude Start
  - Anytime After ~ 2 Hours
    - 1 lbm/sec Recirculation of LOX and H_2 for ~ 90 Minutes Prior to Restart
    - Thermal Control Paint on LOX Turbomachinery and Ducting
    - Component Heating Required
      - Main Fuel Valve Discharge/Coolant Control Valve
      - Oxidizer Preburner Oxidized Supply Duct
  - Restart as Soon as One Hour Possible with Additional Component Heating

SSME Upper Stage Use
Stage Impacts

The stage requirements for using the SSME on an upper stage engine are shown on the facing page. The pressures are 40 psia for the LOX and 32 psia for the H_2. As was shown on previous charts, the pressure needed can be traded against the temperature of the supplied propellants and, to a degree, the details of the start. If a start to a power level between 100% and 109% is needed, either a ramped start (first to 100%, then as acceleration head is produced, to 109%) or a higher pressure can be used.

The stage will also have to supply recirculation flowrates of about one lbm/sec for up to 90 minutes for both the LOX and H_2. It may be possible to integrate this flow into a stage pressurization scheme. If not, then a low pressure dump must be present and the fluid penalties are about 5400 lbm per propellant.

TA3–0295A

SSME Upper Stage Use

Stage Impacts

- **Pressures**
  - **LOX $\geq$ 40 psi**
  - **$H_2 \geq$ 32 psi**
  - **Higher Pressures Allow Immediate Ramp to Higher Power Levels**
    - **At These Pressures Start May Require Ramp to an Intermediate Power Level (~100%) Followed by a Wait for Acceleration Head and Then Ramp to 109%**

- **Recirculation**
  - **1 lbm/sec Required on Both LOX and H2 Sides**
  - **Could Possibly be Integrated Into Stage Pressurization Scheme**
  - **May Need Low Pressure Dump**
    - **Stage**
    - **Overboard**

SSME Upper Stage Use
SSME Impacts

The impacts on the SSME to allow its use as an upper stage engine are minor. Recirculation capability must be provided, but the H2 side already has more than enough capability. The LOX side has a current flow path but the flow is currently dumped. A recirculation pump would be needed.

The sequencing of the valves during the start must be modified and the changes verified.

Thermal control paint is needed on the LOX side and advantageous on the H2 side to allow start at lower tank pressures throughout the orbit (including the worst case on the solar side).

Lastly, direct component heating is required of some small, low thermal mass components. Because the mass is low a simple solution such as electric blankets may be adequate.

SSME Upper Stage Use
SSME Impacts

- Recirculation
  - H_2 Has Recirculation System with Higher Than Needed Flowrate Capability
  - LOX Has System to Run Propellant But Then Dump the Propellant
    - Recirculation Pump Needed
- Valve Control Changes
  - New Sequencing of Positions and Ramp Rates must be Implemented and Verified
- Paint
  - Thermal Control Paint Needed on LOX Turbomachinery and Ducting
  - Thermal Control Paint Advantageous on Fuel Turbomachinery and Ducting
- Heating of Components Possible with Direct Contact Heaters
  - Electric Blankets

SSME Upper Stage Use
Development Plans

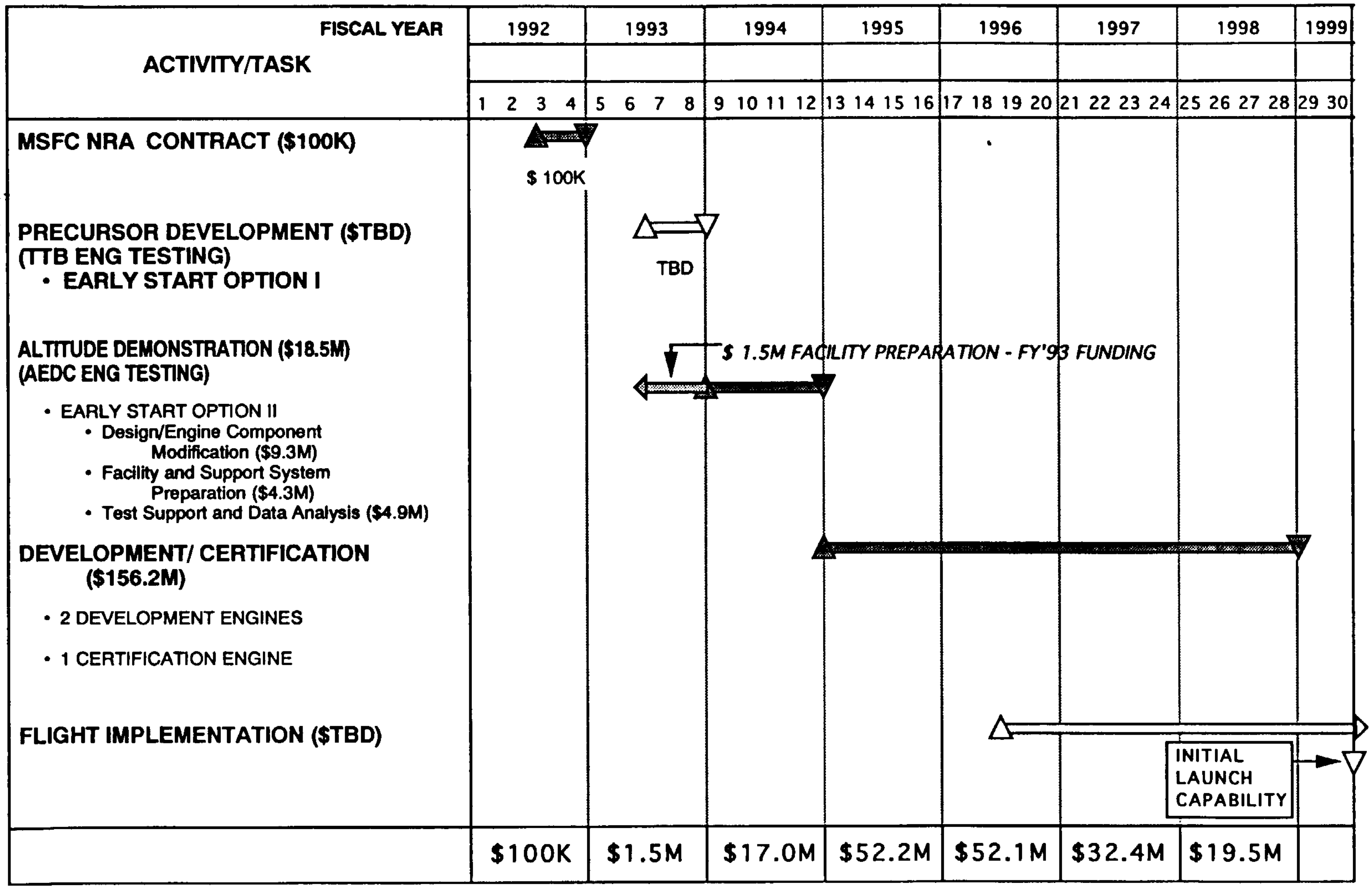
The program needed to develop and certify the SSME for upperstage application can be accomplished with low risk and relatively low cost compared to a new engine program. Key testing can be accomplished in a minimal cost demonstration program to provide an early understanding of the risk involved before development and certification of SSMEs for upperstage use is started.

The ground rules and assumptions which were utilized for estimating the program costs are as follows: All costs are in Fiscal Year 1992 dollars. The cost of production engines for the new vehicle is not included. The demonstration program and development program are conducted in series and transition immediately from one to another. Engine unit costs are based on a total production rate of six per year. Only minor changes, such as reorificing of igniter propellant feedlines, adding insulation/thermal control paint, reducing insulation on the nozzle, and incorporating a LOX propellant recirculation system are required. Procedural changes for the engine are assumed to be required as well. The engine used for the demonstration is upgraded and used as the first development engine. Propellant costs are not included in the cost estimate as they are typically furnished by the customer. The total program cost of $174.8 million does not include fee.

The schedule assumes that one test stand at the NASA Stennis Space Center is available and that 130 tests are needed between the Demonstration and the Development/Certification phases. A large number of starts are required because many of the parameters being changed on the engine and the propellant feed system influence the start sequence significantly. A low risk incremental test series will be utilized to develop the new start sequence (~ 14 starts) and restart sequence (~ 30 starts) since experience has shown that hardware damage can occur during the start sequence. Once the start and restart sequence are initially defined a series of tests (~ 6 starts) with nominal parameters will be run to demonstrate repeatability. Historically two engines have been used in the past for SSME development phases to address engine to engine variation and properly define off design and envelop operating characteristics. Assuming similar requirements will exist for the upper stage application a two engine test series with 15 starts and 15 restarts each was utilized. The certification unit is a new production engine which has a production schedule of approximately 4 years. Once the engine is available, testing would be conducted with 10 starts and 10 restarts as a certification. If an earlier flight data is required for the program, a used engine could be used for certification testing which could move up the initial launch capability by one and a half years.

The schedule assumes that one test stand at the NASA Stennis Space Center is available and that 130 tests are needed between the Arnold Engineering Development Center and SSC. Assuming production of flight engines occurs 2 1/2 years after the program is initiated, initial launch capability is viable in 5 1/2 years from program start.

SSME Upper Stage Use
Development Plans



NOTE: SHADED ACTIVITIES INCLUDED IN COST ESTIMATES

$ 174.8M TOTAL

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Recommendations for Further Work

TA3-0275

SSME Upper Stage Use
Further Work

The facing page shows the suggested further work which would be useful if the SSME is to be used as an upper stage. Testing, both to verify the start model results and address any questions about moisture in the engine at restart would be the next step. Additional engine capabilities should be examined if the engine is used for an upper stage: higher area ratio nozzles, expanded controller and new actuator.

The vehicle/engine interface will need to be defined, but the detail must await a vehicle and mission choice.

SSME Upper Stage Use
Further Work

- Demonstration Testing Options
  - Verify Capability
  - Address Issues
- Enhanced Capabilities for Upper Stage Use
  - Nozzle Expansion Ratio Increase Assessment
  - Expanded Engine Controller Functions
  - Upgrade Engine Configuration
    - EMA
    - Single Pneumatic Fluid Purges
- Engine/Vehicle Integration
  - Stage Pressurization/Engine Recirculation System
  - Impacts of Installation Details on Thermal Environment

TA3–0297a

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Eric Stangeland, Daniel Levack

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6633 Canoga Ave
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13. ABSTRACT *(Maximum 200 words)*

The main objective of this study was to determine viable methods for starting the SSME in an altitude environment and restarting it in an orbital environment with minimum changes in utilization of the engine system or hardware.

The study concluded that the use of the SSME in an upper stage is feasible with minimal changes to the engine systems.

The altitude start case requires only a change in the valve sequencing during start and reorificing of the ASI lines. Inlet pressures can be moderately low at 40 psia for the LOX and 32 psia for the H2.

The orbital restart case adds the need to recirculate propellant and thermal control paint (to keep the turbomachinery inlets cold to minimize the tank pressures needed), and the need to heat two small components (to maintain acceptable mixture ratios during the early part of the start). These actions allow start anytime after ~120 minutes. Earlier starts (~one hour) are also possible but would require additional component heating for mixture ratio control during the early portion of the start sequence.

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ROCKETDYNE

Rockwell International

Rocketdyne Division
Rockwell International Corporation
6633 Canoga Avenue
Canoga Park, California 91303